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Subj: ONR Grant# N00014-08-1-0843, "North Pacific Acoustic Lab"

Encl: (1) Final Technical Report for Subject Grant
(2) SF298 for Enclosure

Enclosure (1) is the Final Technical Report for the subject grant. Enclosure (2) is the SF 298 form. These documents constitute the Final Technical Report and deliverable for ONR Grant# N00014-08-1-0843.

cc: Grant & Contract Administrator, APL-UW
Office of Sponsor Programs, UW
ONR Seattle – Evan Wood and Kyoohui Beal
Naval Research Laboratory (hard copy with SF 298)
Defense Technical Information Center (electronic files with SF298)

APL - North Pacific Acoustic Laboratory

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To design and conduct an experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

NPAL employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. The NPAL network, operated and maintained by APL-UW, provides an actual laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The network consists of the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the locations of acoustic hydrophone arrays in the NPAL network.

The second avenue includes highly focused, comparatively short-term experiments. We are currently planning a major experimental effort in the Philippine Sea. Again the primary institutions will be APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT). Earlier this year a Pilot Study/Engineering Test was conducted in the Philippine Sea to characterize the environment and to test new hardware and software systems. During this effort we also provided support to researchers from the Marine Physical Laboratory (MPL) who are supported by the signal processing code of ONR. The main experimental effort in the Philippine Sea will begin in the Spring of 2010, and is outlined in Figure 2.

As we have prepared for the next major experiment, funding from the Defense University Research Instrumentation Program (DURIP) has provided significant support. In particular, this report includes activities funded by two DURIP grants (N00014-08-1-0797 and N00014-08-1-800).

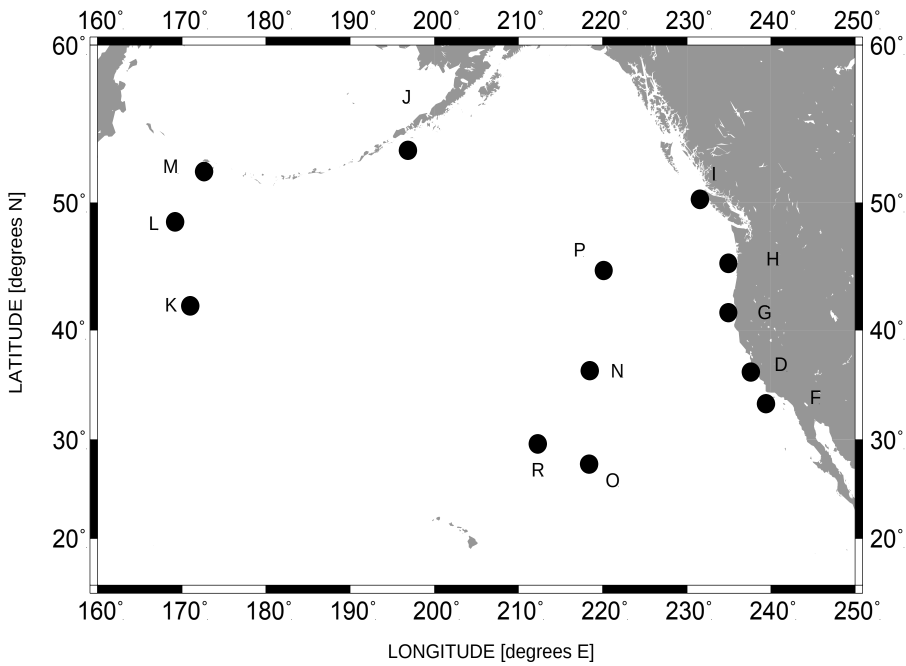

Figure 1. The NPAL hydrophone array network. The locations of arrays identified by the letters R, D, E, and F are exact. The other locations are notional. The entire network is controlled and monitored from APL-UW.

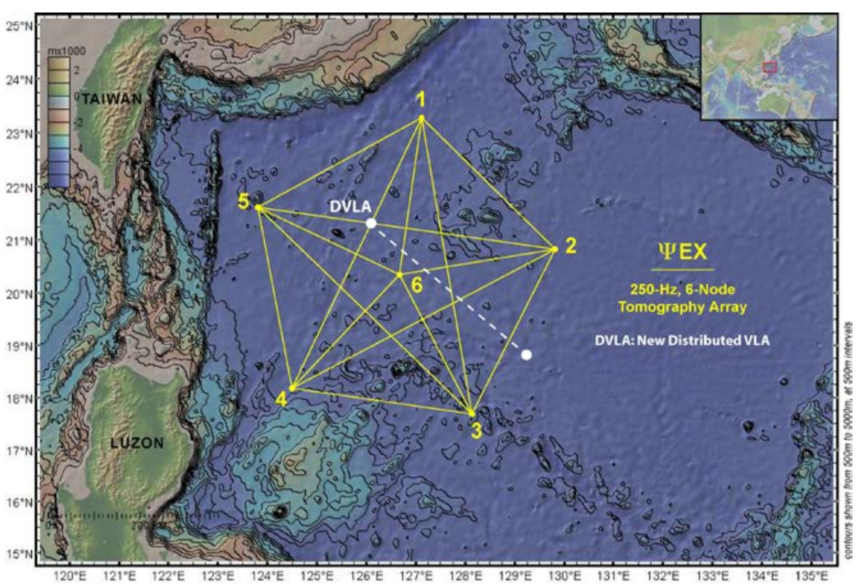

Figure 2. The 2010 Philippine Sea Experiment; the yellow lines are tomography paths between acoustic transceivers, the DVLA is a full water column hydrophone array, and the dashed white line is a 500 km path for continuous broadband transmissions along which extensive environmental data will be collected.

WORK COMPLETED

NPAL Acoustic Network. A paper titled "Long-Time Trends in Low-Frequency Oceanic Ambient Noise along the Western North American Coast" was revised and submitted to the Journal of the Acoustical Society of America. A paper titled "A decade of acoustic thermometry in the North Pacific Ocean" was published in the Journal of Geophysical Research.

LOAPEX Analysis. The Long-range Acoustic Propagation EXperiment (LOAPEX) was conducted by APL-UW in 2004 and is still producing journal articles. A paper titled "LOAPEX: The Long-range ocean acoustic propagation experiment" was published in the IEEE Journal of Oceanic Engineering. A paper titled "The interference component of the acoustic field in the Long-Range Ocean Acoustic Propagation Experiment" was published in the Journal of the Acoustical Society of America. A paper titled "Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation" was published in the Journal of the Acoustical Society of America.

Philippine Sea Pilot Study/Engineering Test. The APL-UW portion of the Philippine Sea Pilot Study/Engineering Test, known as PhilSea09, was conducted between 14 April and 1 May 2009. The exercise area is shown in Figure 3.

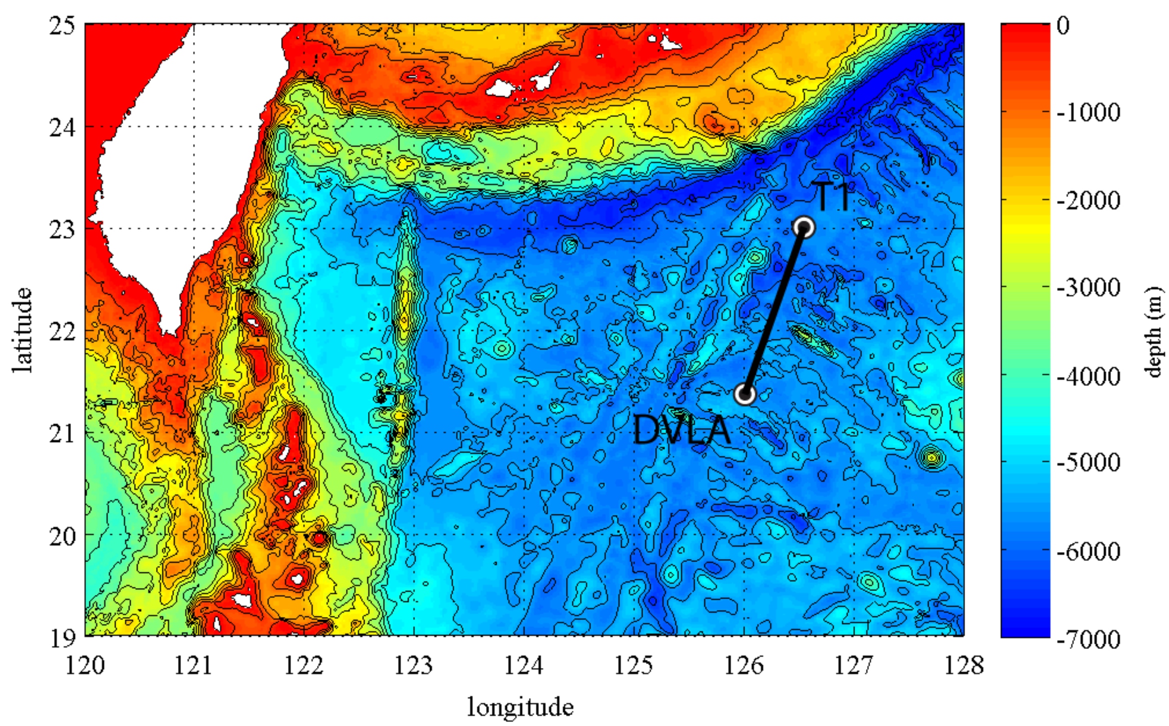

Figure 3. The exercise area for PhilSea09.

The DVLA, indicated in Figure 3, was a prototype for the full-water-column array and included an axial sub-array and a near-bottom sub-array. APL-UW suspended acoustic sources at ranges of 47 and 107 km from the DVLA and collected environmental data along the path (black line) and beyond the DVLA.

The locations of environmental data collected by APL-UW are shown in Figure 4.

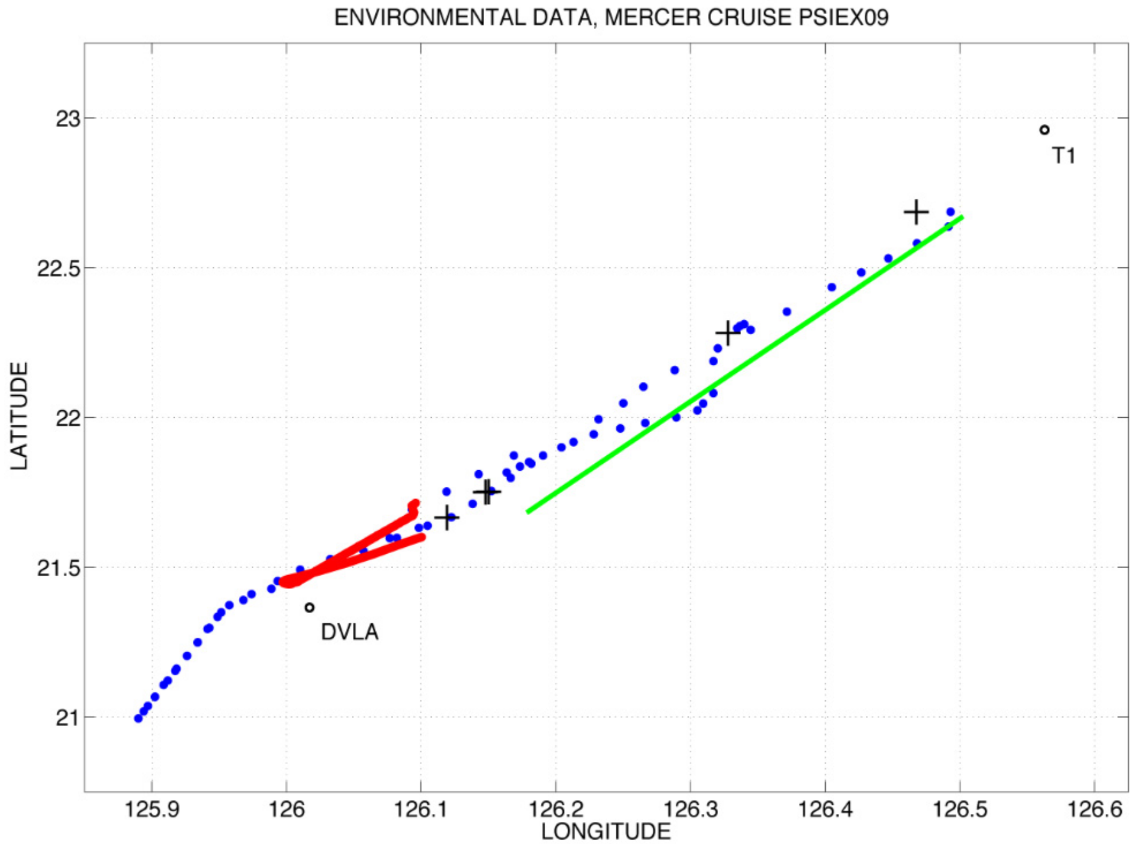

Figure 4. Locations of environmental data collected during PhilSea09 (aka PSIEX09). The blue dots represent the locations of XBT drops, the black plus symbols are locations of conventional CTD casts, and the red and green lines represents paths for the new towed CTD Chain.

The Philippine Sea Experiment (PhilSea10). Conceptual plans for PhilSea10 were finalized in September of this year. SIO will install the tomography array and DVLA in April of 2010 and they will operate for a full year until their recovery in 2011. APL-UW will conduct suspended source operations at a range of 500 km from the DVLA totaling 110 hours of continuous transmissions at a depth of 1000 m. The transmissions will be divided equally between the HX source operating at a center frequency of 80 Hz and the MP source operating at a center frequency of 260 Hz. The HX source will also be used at 50 Hz while drifting at a depth of 150 m between ranges of 25 to 35 km from the DVLA. In addition, APL-UW will conduct extensive CTD casts between the DVLA and the 500

km test position and also tow the CTD Chain along this path. During July of 2010 the MIT/WHOI group will tow a J-15 acoustic source at various ranges from the DVLA.

Instrumentation for the Philippine Sea Experiment – DURIP (N00014-08-1-0797). This DURIP grant provided a number of instruments to improve the reliability and safety of our field work. Signal durations in the Philippine Sea were extremely long, on the order of 50 hours. The generation of long-duration, high-power acoustic signals required new instrumentation including a broad-band amplifier and low-level signal generation hardware and software. The detailed design of the experiment (e.g., depths and ranges to the other assets) required extensive computer simulations to be conducted with a parabolic equation acoustic propagation code, and a numerical model of the effective acoustic scattering. To accomplish these simulations a small computer cluster was purchased. The requirement to precisely navigate the location and velocity of the projectors was met with an acoustic tracking system. The control and data logging features of this system also provided for the recording of the projector internal temperature and pressure.

To accomplish these long transmissions some new instrumentation components were required. The first was a new power amplifier. Our existing power amplifier was damaged in an electrical storm and was not capable of providing power across the entire frequency band of the HX and MP transducers. An L50 power amplifier from Instruments Inc. was purchased to meet our requirement.

In general, the type of acoustic transmissions used in our work are either broad band phase-coded, maximal-length binary sequences, or source compensating frequency-multiplexed non-linear slides. These signals are generated from specialized hardware and software. Our existing signal generation equipment was based on a 15-year-old 80486 PC running DOS, an obsolete National Instruments data acquisition (DAQ) board, and a custom discrete logic timing board. The signal waveform output must be synched to a precision GPS clock, providing microsecond timing accuracy, via the timing board, the DAQ, and custom software. Components which have failed over the years have been replaced with parts salvaged from other systems. There were no more such spare salvaged components available. All components, with the exception of the timing board, were utterly obsolete, so there was no option to purchase replacement parts. Continuing dependence on this system would result in a total loss of transmission data in the increasingly likely event that any aging part should fail. A replacement signal generation system was required.

We upgraded our signal transmission capability by replacing our aging and obsolete 80486/DOS computers with 80686/Linux systems. A key component of this upgrade has been replacing the old National Instruments AT-MIO-64F5 data acquisition cards with National Instruments PCI-6071E cards (purchased with an earlier DURIP grant) and finding/installing/integrating corresponding device drivers. We selected the open-source drivers from COMEDI over the new National NIDAQmx Linux drivers because (a) the National driver was essentially ported from the COMEDI community, and (b) the

COMEDI driver is delivered as source code, whereas the source for the National driver is proprietary and not available. Source code availability was critical during development, as it enabled us to match our requirements through to the hardware capabilities by rendering transparent the operations from user space to kernel space to hardware features documented in the NI manuals.

The goals of our experimental method were to combine high resolution environmental data with precisely controlled geometries for acoustic transmissions. The accurate navigation of our deployed sources is a critical element in computing coherence functions for our received signals. We needed to be able to separate signal de-coherence caused by source-motion Doppler, from that due to the ocean variability related Doppler. The best and most straightforward method of navigation down to 1000 m depths is an acoustic tracking system. In PhilSea09 we used existing acoustic transponders and deployed them on the bottom about our source positions and with this DURIP developed tracking system that interrogates the bottom-mounted transponders and receives their replies. This tracking system was located in the immediate vicinity of the acoustic projector. The heart of the system is a Teledyne Benthos ATM-885 modem board that comes with a suitable tracking transducer, and a Persistor CF2 controller and data logger. As an inexpensive method of obtaining the source depth, we incorporated a pressure sensor on the tracking system pressure case. We purchased a Paroscientific pressure transducer and integrated it into the system. This data was recorded in the tracking system data logger and sent to the surface via the fiber link. There was some concern about the internal temperature of the acoustic sources. Because of the very long transmission durations it was considered prudent to have a method of monitoring the internal temperature of the sources. To this end, a small temperature probe was mounted inside the source transformers and the resulting signal was sent to the tracking system pressure case where was recorded and sent to the surface via the fiber link. All tracking and sensor data were recorded in the tracking system pressure case so that breakage of the optic fiber would not be catastrophic.

Towed CTD Chain – DURIP (N00014-08-1-0800). A major focus of the Philippine Sea Pilot Study/Engineering Test was a study of the physics related to the performance of acoustic propagation models and the models that ultimately describe the ocean sound speed and its variability. The Philippine Sea is a highly energetic region and a detailed knowledge of this environment was required to develop and test both environmental and acoustic propagation models. Variability in the sound-speed structure due to internal waves, neutrally buoyant sound-speed perturbations, internal tides, and mesoscale eddies and fronts will produce large fluctuations in the received signals reducing the temporal and spatial coherence. Although we sampled the water with conventional in-situ instrumentation such as conventional CTDs and XBTs, the best and a more synoptic measurement could be obtained by deploying a Towed CTD Chain directly along our propagation path. The goal was to eliminate uncertainty about the sound-speed description when comparing acoustic data and model outputs. To this end we ordered a Towed CTD Chain System from ADM-Electronik (Germany). The main elements of the system are illustrated in Figure 5.

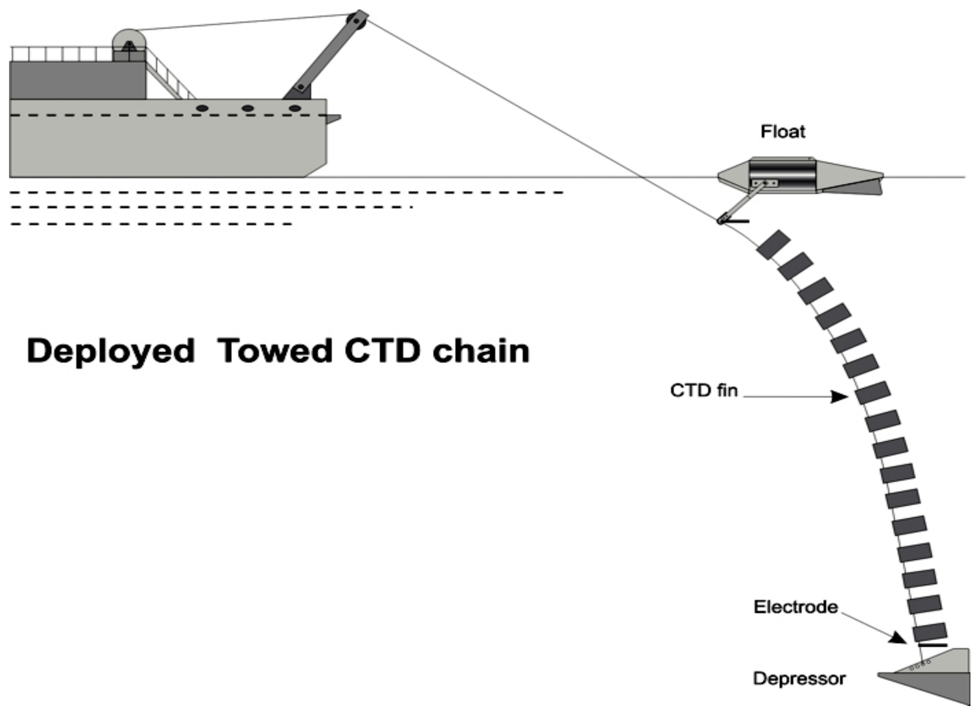

Figure 5. Main components of the Towed CTD Chain.

RESULTS

The addition of the Optical/Electrical/Mechanical for suspending our acoustic sources allowed several new capabilities. For example, temperature sensors in the acoustic sources indicated that the sources were not overheating during the very long transmission sequences. In addition, pressure sensors near the sources provided very accurate depth information and a hydrophone channel allowed us to monitor and calibrate the source without having to suspend another cable from the ship. Finally, an acoustic navigation system, controlled over the fiber, but located near the sources, provided location information on the sources while they were deployed. Figure 6 illustrates the quality of the acoustic tracking that was achieved. This figure compares acoustic tracking (the thin line in each frame) with positions based upon the leased C-Nav GPS system. The C-Nav GPS system has an accuracy of 10 cm and its antenna was placed directly over the block from which the acoustic source was suspended. The upper two frames in Figure 6 compare the east and north tracking solutions for a period of about 15 minutes. The slight phase shift between the acoustic and GPS data is expected because the source is several hundred meters below the ship and it takes a short time for the source to “feel” the ship motion. The bottom frame compares the vertical motion of the source as computed acoustically with the vertical motion of the GPS antenna over a period of only 120 seconds. Because the source is suspended with a steel cable they move up and down together. The location as determined by the GPS was shifted to overlay with the acoustic data. The heaving of the ship can be seen clearly in both data sets.

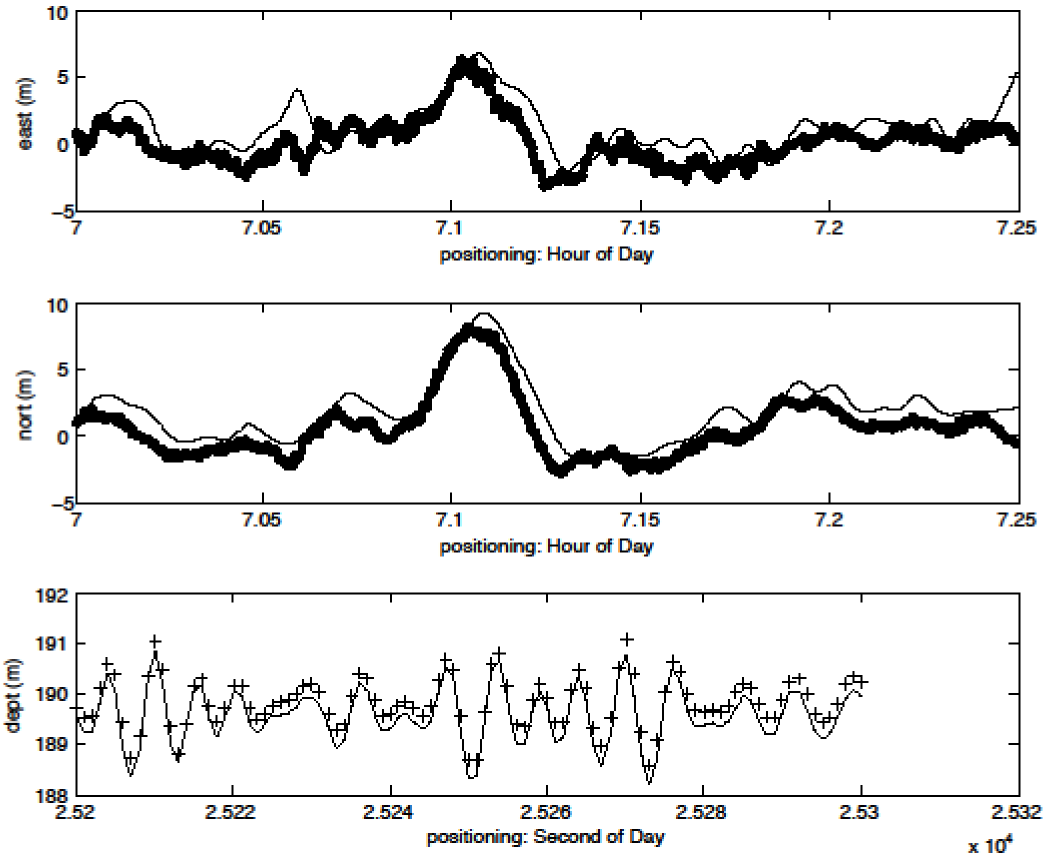

Figure 6. A comparison of source tracking via acoustics (thin line) and the C-Nav GPS system. The top frame is motion in the east-west direction, the middle frame in the north-south direction, and the bottom frame in the vertical direction.

During the Pilot Study/Engineering Test (PhilSea09) acoustic transmissions were performed at two ranges from the DVLA, 47 and 107 km. Figure 7 presents a reception from the MP source on the DVLA at a range of 47 km. The vertical axis is depth, and the horizontal axis is time in seconds. In effect, the figure shows a time front sweeping across the axial sub-array. The reception shown includes only one M-sequence. Normally, many sequences would be averaged together coherently to increase the signal-to-noise ratio, but even a single sequence is clearly observed here. In this case the MP source was at a depth of 1000 m. No corrections have been made yet for the motion of the array or the motion of the source. Once these corrections are made, a movie of the receptions over several hours will reveal the effect of ocean sound speed perturbations on the acoustic time front. The dark bands in the figure reveal areas on the DVLA where the hydrophones are separated by 75 m instead of the 25-meter spacing for the central part of the axial sub-array.

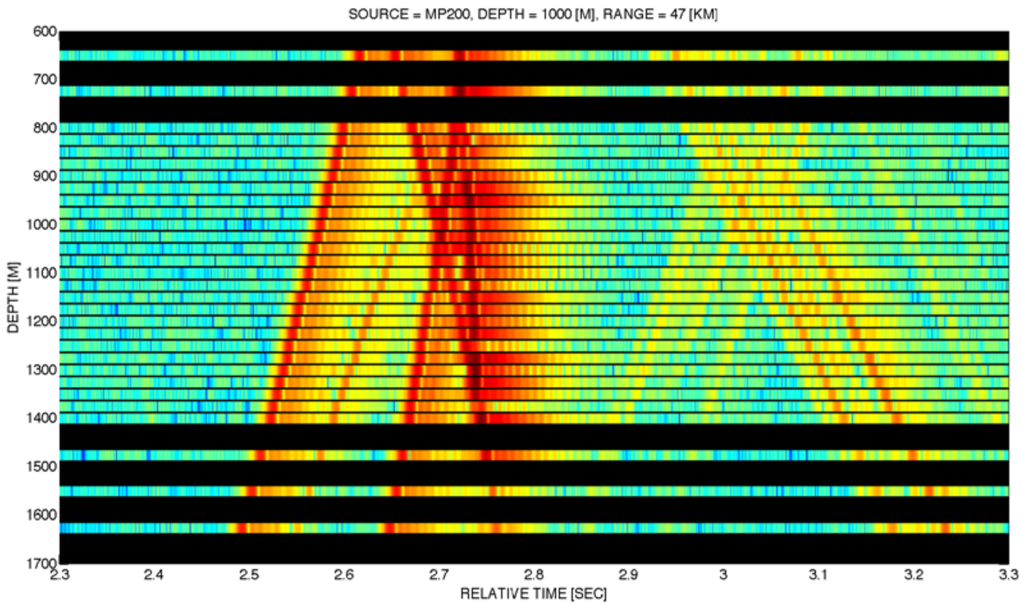

Figure 7. A time front reception on the axial sub-array of the DVLA. The source was the MP source at depth of 1000m at a range of 47 km. Only one M-sequence is displayed in this reception. The source band width is approximately 230 to 330 Hz.

Figure 8 presents results from typical CTD data collected during a) LOAPEX, and b) PhilSea09.

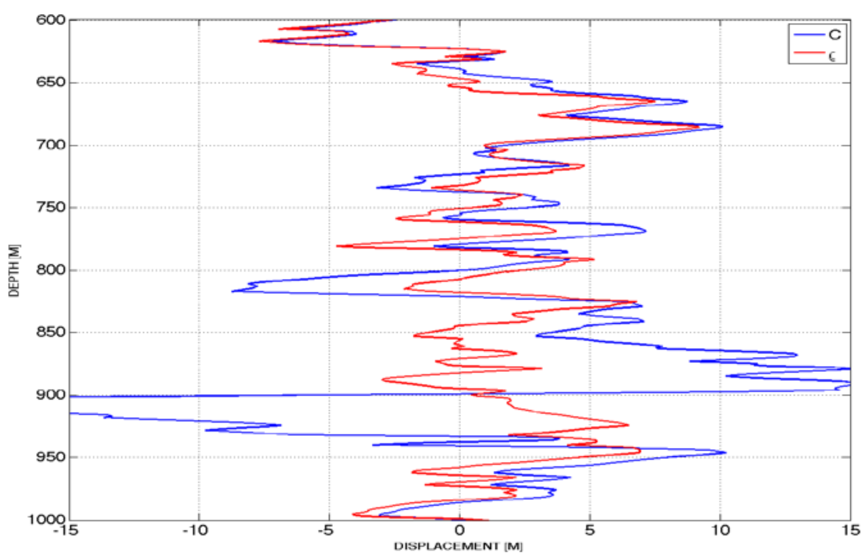

Figure 8a. Density displacements (red) and sound speed displacements (blue) vs. depth from a typical CTD cast taken during LOAPEX.

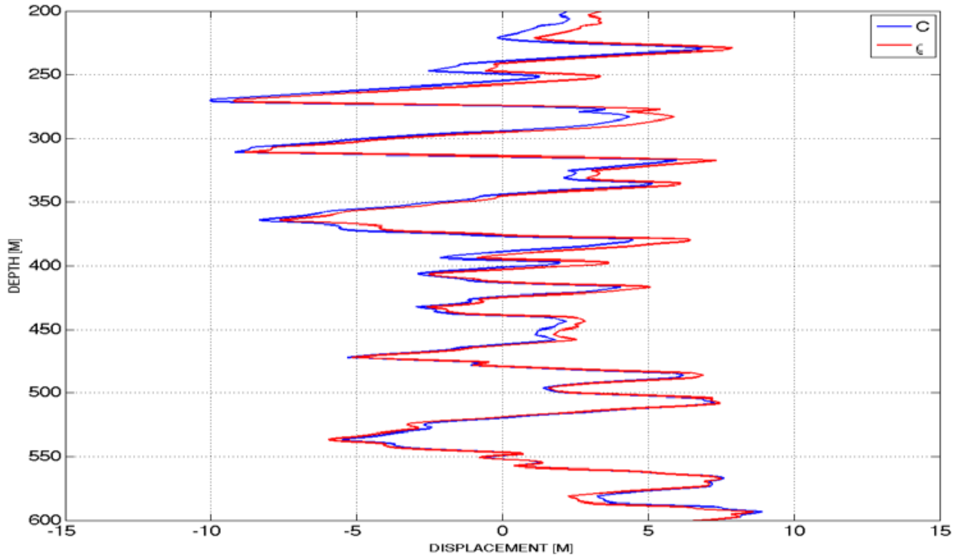

Figure 8b. Density displacements (red) and sound speed displacements (blue) vs. depth from a typical CTD cast taken during PhilSea09

Due to the fact that the Philippine Sea is a highly dynamic region of the global ocean, we expected to find a significant internal wave field and a significant spice field. Spice refers to water masses that are density compensated but have an altered sound speed compared to the standard water mass at the same depth. For example, a water mass that is warmer and saltier than the surrounding water will have a different sound speed, but may have the same density, and therefore be stable at that depth. The relative displacements of density and sound speed shown in Figure 8a from LOAPEX allow one to infer that significant spice is present. The similar data in Figure 8b from PhilSea09 do not suggest the presence of spice.

The difficulty in quantifying spice is due to the fact that it does not propagate as internal waves do. For internal waves, a single mooring with many sensors throughout the water column can provide a great deal of information about internal waves in the region of the mooring. The horizontal spectrum of spice cannot be measured this way. To this end we deployed and towed the CTD Chain illustrated in Figure 5.

The CTD Chain used in PhilSea09 has 88 individual CTD fin instruments on the inductive cable. A deck interface sent a signal to all 88 fins at once causing each fin to simultaneously lock in measurements of conductivity, temperature, and pressure (depth). The interface then polled each fin, one at a time, to retrieve its data. This entire process was repeated every two seconds. Figure 9 presents results from a tow approximately 10 nm miles long. The figure plots ocean temperature as a function of pressure (depth) and the tow period which lasted about 2.5 hours.

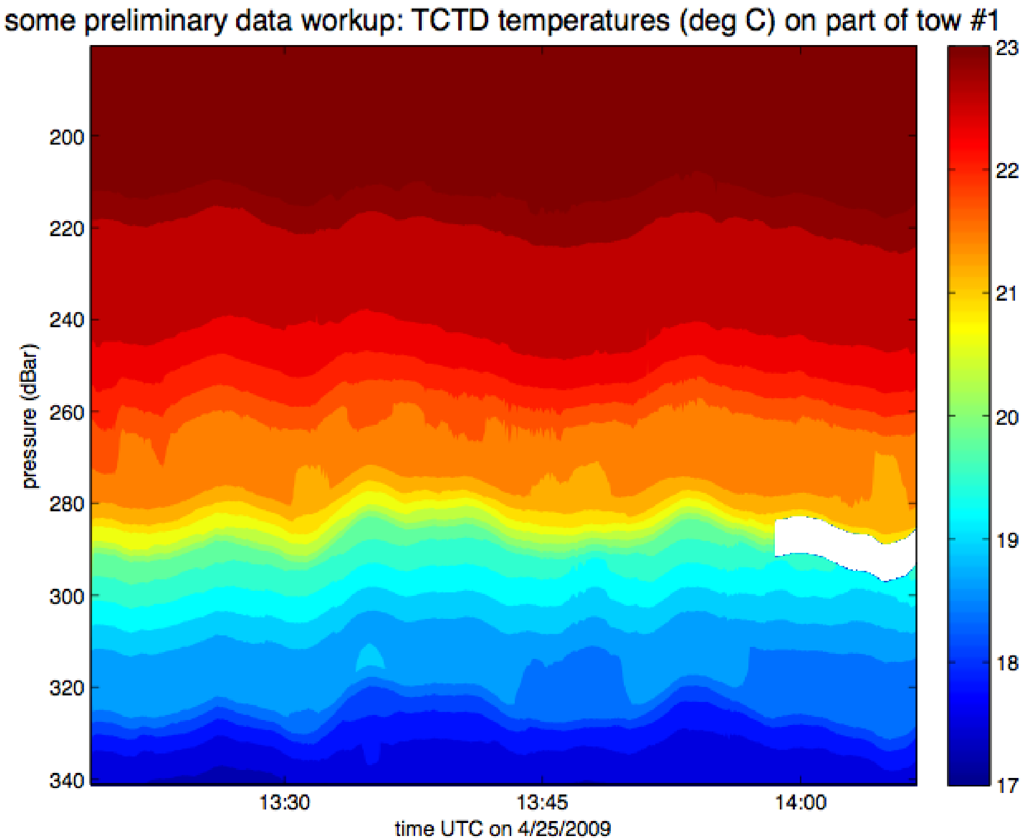

Figure 9. Towed CTD Chain temperature data from PhilSea09 vs. pressure (depth) and the tow period (about 2.5 hours). The temperature scale at right is in degrees Centigrade.

As a back up to the CTD casts and the towed CTD Chain data, roughly 100 XBT drops were made during PhilSea09. XBT probes measure the water temperature as they fall through the water column. The temperature data is sent to the surface on a very fine copper wire. Unfortunately the probes are not highly accurate and any estimates of the sound speed require an assumption about the salinity profile. Furthermore, the depth of the temperature data is based upon an assumption about the rate at which the probe falls through the ocean. This rate can be affected by the currents in the water and by the friction on the spools which deploy the copper wire. We used primarily two types of XBT probes during PhilSea09, T5s and T7s. T5s work to a depth of 1800 meters, while T7s work to a depth of 750 meters. Figure 10a compares temperature data versus depth for both T5 (green) and T7 (blue) probes. Also in the figure is a dotted red line that shows the temperature results from a PhilSea09 CTD cast. There is a significant difference between the T5, T7, and CTD temperature data. Figure 10b shows the same data after fall rate corrections have been made for the XBT probes.

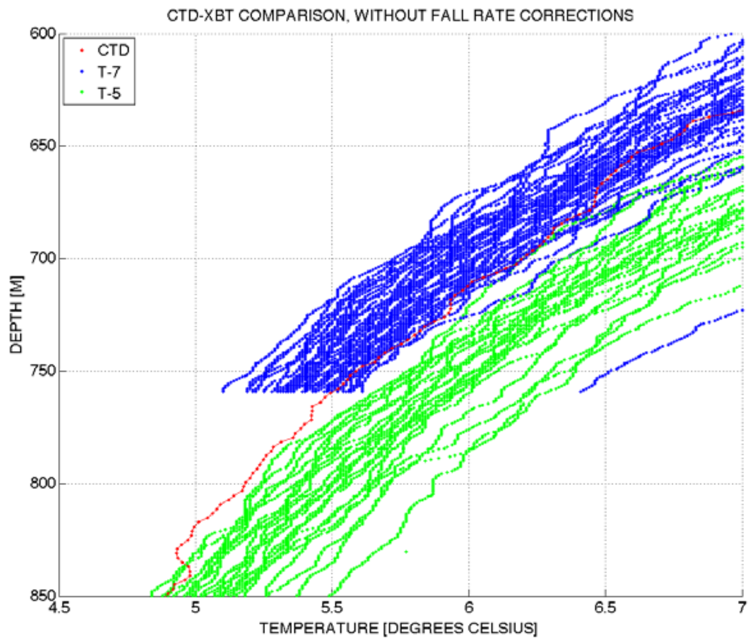

Figure 10a. Uncorrected Philsea09 XBT data. T5 (green) and T7 (blue) XBT temperature data vs. depth compared to temperature data from a CTD cast (red).

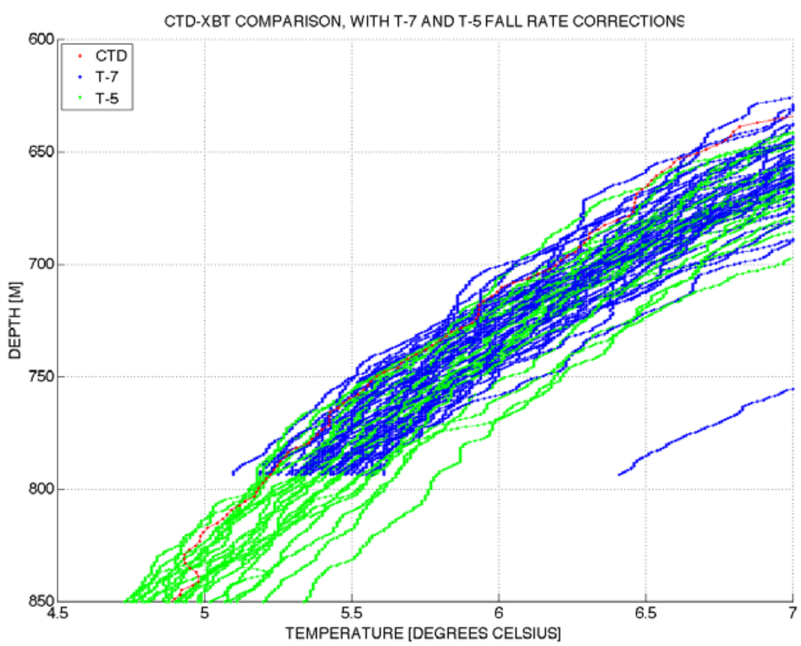

Figure 10b. Corrected PhilSea09 XBT data. T5 (green) and T7 (blue) XBT temperature data vs. depth corrected for fall rate. CTD data (red).

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

RELATED PROJECTS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), S. Flatté (UCSC), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW), V. Ostachev (NOAA/ETL), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), M. Wolfson (APL-UW), G. Zaslavsky (NY Univ.), and others. In addition, we have begun close collaboration with Gerald D'Spain who is funded by the signal processing code of ONR.

PUBLICATIONS

Stephen, R. A., Bolmer, S. T., Dzieciuch, M. A., Worcester, P. F., Andrew, R. K., Buck, L. J., Mercer, J. A., Colosi, J. A., and Howe, B. M., (2009). Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation, *J. Acoust. Soc. Am.*, **126**, 599-606. [refereed]

Mercer, J. A., Colosi, J. A., Howe, B. M., Dzieciuch, M. A., Stephen, R. A., and Worcester, P. F., (2009). LOAPEX: The Long-range Ocean Acoustic Propagation EXperiment, *IEEE J. Ocean. Eng.,* **34**(1), 1-11. [refereed]

Dushaw, B. D., Worcester, P. F., Munk, W. H., Mercer J. A., Howe B. M., Metzger, Jr. K., Birdsall,T. G., Andrew, R. K., Dzieuch, M. A., Cornuelle,B. D., and Menemenlis, D., (2009), A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.,* **114**, C07021, doi:10.1029/2008JC005124 [refereed]

Grigorieva, N. S., Fridman, G. M., Mercer, J. A., Andrew, R. K., Howe, B. M., Wolfson, M. A., and Colosi J. A., (2009), The interference component of the acoustic field in the Long-Range Ocean Acoustic Propagation Experiment, *J. Acoust. Soc. Am*., **125** (4), 1919-1929. [refereed]

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

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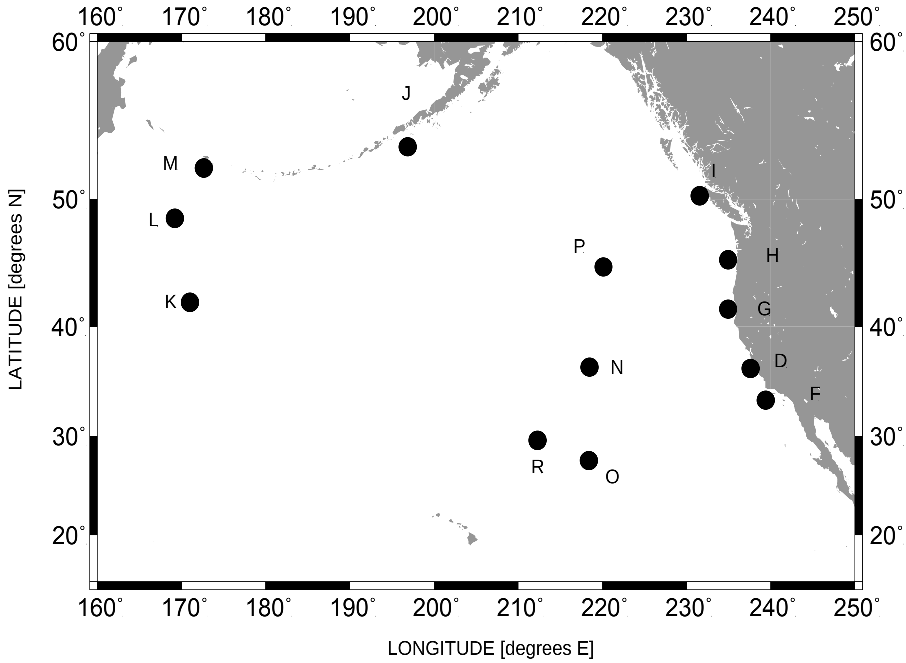
APPROACH

NPAL employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. The NPAL network, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The network consists of the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the locations of acoustic hydrophone arrays in the NPAL network.

The second avenue includes highly focused, comparatively short-term experiments. We have recently completed an experiment in the Philippine Sea called PhilSea10 [1]. The primary institutions were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT). Analysis of environmental data from PhilSea10 has already begun, but the analysis of acoustic data will have to await the recovery of the receiving array in the Spring of 2011. The primary features of PhilSea10 are outlined in Figure 2.



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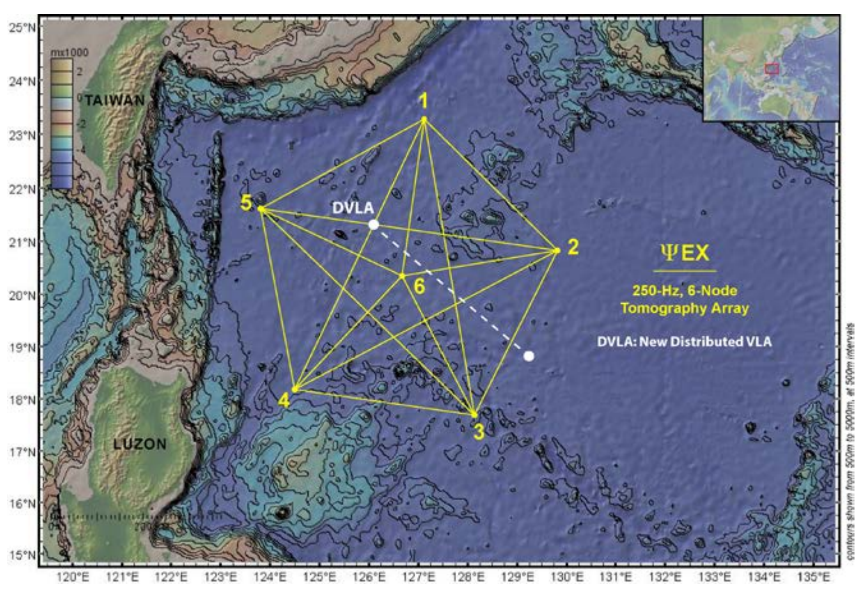


Figure 2. The 2010 Philippine Sea Experiment; the yellow lines are tomography paths between acoustic transceivers, the DVLA is a full water column hydrophone array, and the dashed white line is a 500 km path for continuous broadband transmissions along which extensive environmental data were collected.

WORK COMPLETED

NPAL Acoustic Network. A paper titled "Long-Time Trends in Ship Traffic Noise for Four Sites off the North American West Cost" [2] has been submitted for publication in the *Journal of the Acoustical Society of America*. Measurements from four of our network hydrophone arrays located just off the North American west coast permitted extensive comparisons between "contemporary" low frequency (25-50 Hz) traffic noise collected over the last decade to measurements made in the mid-1960s. The exact same locations and underwater equipment were used in the comparison. Although ambient noise in the 25-50 Hz band had increased roughly 10 dB since the 1960s, linear trend lines of the contemporary traffic noise (durations of the past 6 to 12 years) indicate that the current levels are either holding steady or decreasing at three of the four sites.

The NPAL network is autonomous and can be controlled remotely from APL-UW; however, maintenance is sometimes required. Communications from the shore site located at Barbers Point, HI were disrupted when our broad band carrier switched from a 3G to a 4G protocol. A new modem was installed and communications resumed. A failure in the Ling Amplifier at the Kauai site and a broken underground cable were also repaired by APL-UW personnel.

Although ambient noise products are not considered classified, they are processed in a classified facility. A significant effort was put forth this year to re-certify this facility. A request by Mike Brown (RSMAS) for data from Barbers Point was delayed by the re-certification effort.

LOAPEX Analysis. APL-UW conducted the Long-range Ocean Acoustic Propagation EXperiment in 2004 between Hawaii and California [3]. The data continue to produce presentations and papers. For example, LOAPEX deployed four Ocean Bottom Seismometers to receive transmissions from our ship-suspended acoustic source. A JASA paper last year [4] described the unexplained receptions. A presentation [5] this year suggests that the deep seafloor arrivals (out to 3200 km range) that are dominant on the geophones but absent on the deep hydrophones may be the result of seafloor interface waves.

Two other papers, based upon LOAPEX acoustic transmissions have been submitted to the *Journal of the Acoustical Society of America.* They are "A modal analysis of the range evolution of broadband wavefields in a deep-ocean acoustic propagation experiment I: low mode numbers" [6], and "A modal analysis of the range evolution of broadband wavefields in a deep-ocean acoustic propagation experiment II: mode processing deficient array measurements" [7].

PhilSea09, PhilSea10, and LOAPEX utilized acoustic sources that were suspended from research vessels to depths as much as 1 km. In order to keep source motion from contaminating estimates of de-coherence due to the ocean, it was necessary to develop source tracking methodology based on several instruments. These included acoustic tracking, a GPS system that incorporated real-time corrections for satellite clock and

ephemeris errors, acoustic Doppler profilers, and localized current meters. The results of the analysis of source motion during LOAPEX have been accepted for publication in the *IEEE J. Ocean. Eng.* in a paper titled "Ship-suspended acoustical transmitter position estimation and motion compensation" [8].

PhilSea10-Experimental Design. The design of the APL-UW portion of PhilSea10 was relatively simple. The 500-km experimental path is shown as a dashed white line in Figure 2. The principal elements of the experiment were as follows: 1) a 55-hour continuous transmission with the MP acoustic source from a site 500 km from the DVLA (vertical hydrophone array) and at a depth of 1,000 m, 2) a tow of the CTD Chain along the path toward the DVLA, 3) a tow of the HX acoustic source at a depth of 150 m at ranges between 25 and 43 km from the DVLA, and 4) a series of CTD casts every 10 km from the DVLA back to the original site 500 km away, and 5) a 55-hour continuous transmission with the HX source at a depth of 1000 m. The details of the cruise are contained in the cruise report [1].

PhilSea10-System Development. Although the design of PhilSea10 was rather straightforward, several complex systems were developed and deployed. The HX acoustic source was damaged during PhilSea09 and required significant repairs.

Three low frequency acoustic underwater projectors were purchased from Alliant Techsystems in 1993 to support the ATOC (Acoustic Tomography of Ocean Climate) project. These projectors, designated type HX-554, consist of 10 staves configured in a cylindrical array approximately 30 inches in diameter by 45 inches high, not including the tuning transformer and pressurization system. Each stave is a 90-element bender bar transducer. When deployed the cavity inside the cylinder is filled with compressed air to provide the appropriate acoustic compliance-versus-sea pressure at depth. Projectors S/Ns 001 and 003 were installed at select sites off the California coast and north of Kauai, respectively.

The third projector, S/N 002, which was to be a spare, was initially configured for an experiment on FLIP in 1994. This unit was damaged during the FLIP experiment wherein the bars and their stress rod cavities were exposed to sea water. The unit was completely disassembled and the stress rod cavities of the bender bars were flushed with isopropyl alcohol. The projector was then reassembled in the original ATOC configuration and tested but not deployed. It was eventually reconfigured without the ATOC frame and without the outer boot for use as a dipping source. See Figure 3.

While the Kauai installation is still intact and capable of resuming operation the California system has been dismantled though the projector, S/N 001, has not yet been recovered. Recovery of the California projector has been a priority as it would afford a reliable backup to S/N 002. A recovery was scheduled on the *R/V Atlantis* with deep sea submersible *Jason* on board during a transit from San Diego to Astoria, OR in June of 2008. However, due to a combination of inclement weather and engine problems along the way, and the ship's scheduled arrival in Astoria, there was insufficient time to attempt a recovery. Recovery of this projector remains a priority.

Figure 3. HX-554 projector configured as a dipping source.

Figure 4. Bender bar with broken stress rod.

Projector S/N 002 was deployed as a dipping source during PhilSea09 at the site of PhilSea10 scheduled for the spring of 2010 in the Philippine Sea. Soon after the unit was deployed it exhibited a short that could not be corrected on site. As it was being disassembled at the Laboratory it became evident that multiple and catastrophic failures had occurred. A total of four bender bars had at least one broken stress rod (Figure 4). Bender bar S/N 016 (Figure 5) and one other bar had shattered elements.

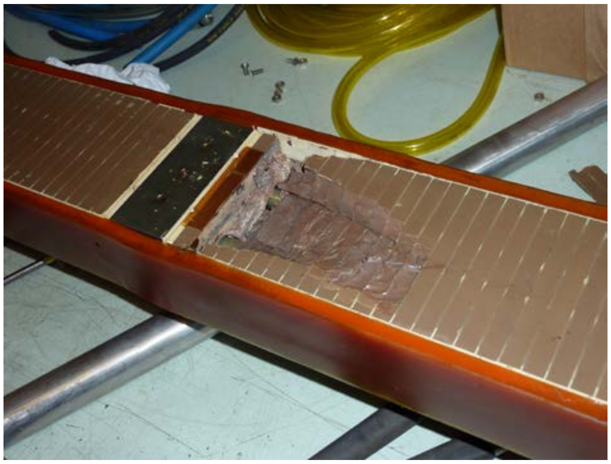


Figure 5. Bender bar S/N 016 showing shattered elements.

Figure 6. Installing bender bar S/N 016 as an inactive stave.

As none of these bars could be repaired or replaced it was decided to reassemble the projector using only five active bars spaced for symmetry. The remaining five bars were installed in order to provide structural integrity and a complete enclosure for proper pressurization but they were not electrically connected. Figure 6 shows a damaged bar ready to be put in place between two active bars. The figure also shows the heavy aluminum spacers that are installed between the bars. The power level for the PhilSea10 experiment was reduced slightly as a safety factor and the projector performed flawlessly during its two deployments.

The other acoustic source, known as the Multi-port or MP source, was also damaged during PhilSea09. A pressure compensation hose to the tuning autotransformer became disconnected and allowed sea water to damage the transformer. Its primary function is to boost the voltage applied to the transducer. Its secondary function is to adjust the power factor of the transducer as seen by the power amplifier. The first version of the system autotransformer was fabricated in 2008 by Coiltron, Inc (Tigard, OR). The damaged unit was returned to Coiltron with instructions to salvage the core and build a replacement autotransformer. The new autotransformer has two tap settings, providing inductances of 220 mH and 300 mH, respectively: both tap settings up-convert the amplifier drive voltage by a factor of 2. The history of system development from 2005 up to this reporting period has been documented in an APL technical report [9].

The two acoustic sources were suspended from the research vessel *REVELLE* on a mechanical/electrical/optical cable. The introduction of optical fibers for PhilSea09 allowed reliable monitoring of the acoustic sources in real time, improved acoustic navigation of the sources, more reliable transponder surveys, and easier deployments of the hardware over the stern of the research vessel. One addition for PhilSea10 involved an optical control line for the gas pressurization system on the HX source. Once this source reaches operational depth, a valve is activated to release air from high pressure cylinders mounted below the source into the interior of the source to improve compliance for the acoustic elements. This valve had been activated by an acoustic command from the ship. This acoustic link was difficult to achieve and confirmation of activation was unreliable. The optical control line solved this problem and was a significant time saver in PhilSea10.

In order to improve the conduct of navigating the sources acoustically and assist the surveying of bottom transducers used in the navigation, a software utility was developed to display relevant data. The snapshot shown in Figure 7 captures an actual display of acoustic survey data taken during PhilSea10. During planned transmissions from the sources, while acoustic navigation was taking place, the display not only provided control of the acoustic interrogator and monitoring of the receptions, it also displayed a readout of the source depth (pressure) and the status of battery power supplies for the subsea electronics. This innovation proved to be a great asset, particularly for maintaining reliable acoustic survey and navigation data. The graphical display easily identifies outliers and allows the channel gains and delays to be quickly reset if necessary to maintain good acoustic data.

An analysis of the acoustic navigation data has been completed and the results are reported in "NPAL 2010 Cruise Tracking Report" [10]. The analysis indicates typical horizontal velocities of the suspended source of 0.02 m/s or less, suggesting that source Doppler should not be a significant issue for Doppler-insensitive statistics.

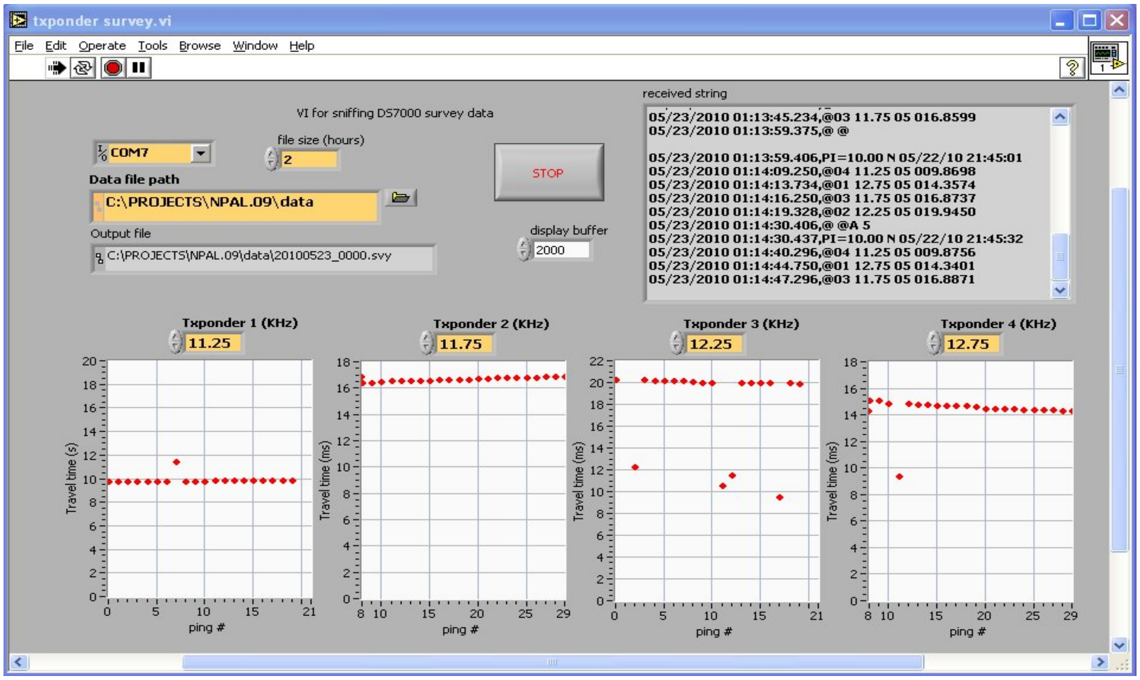


Figure 7. Snapshot of acoustic survey screen.

The hardware and software discussed above were tested in Lake Washington in January 2010. Although actual source transmissions were not allowed, it was possible to determine that all supporting systems were operating normally.

PhilSea10-Towed CTD Chain. The Towed CTD Chain (TCTD) is an 800 m long cable instrumented with 88 sensor fins (originally to be 100 fins but 12 from previous field use were broken and unavailable at the time of our cable assembly); see Fig. 8 for a notional diagram. Each fin has onboard sensors to measure temperature, conductivity, and pressure like a traditional CTD instrument. A traditional CTD is generally cast at one geographic point location while the ship is stopped, yielding very high depth resolution CTD measurements at that single point location. In contrast, the TCTD is meant to yield a relatively high resolution (on the order of 5m both vertically and horizontally), 2D vertical slice of the ocean, with CTD measurements down to 500-600m depth for as far as one wishes to tow the cable. Unlike other towed instruments such as the SeaSoar [11], the TCTD simultaneously takes measurements over the entire depth range every few seconds, resulting in much higher spatial and temporal resolution.

However, while this system's concept is very attractive, and a few much smaller versions of it have been used successfully in the past, including Shallow Water 2006 (SW06) [12,13], the present large-scale version of it has a number of technical problems, both mechanical and electrical. Many mechanical problems were revealed during PhilSea09 and those which could be addressed by APL-UW were resolved, but many problems remained and they greatly constrained the measurements in PhilSea10 and their usefulness. The fundamental problem is a lack of sensor fin response – in SW06

typically 90% of the sensors responded, compared to 20-60% (typically 30%) in the PhilSea10 (Table 1).

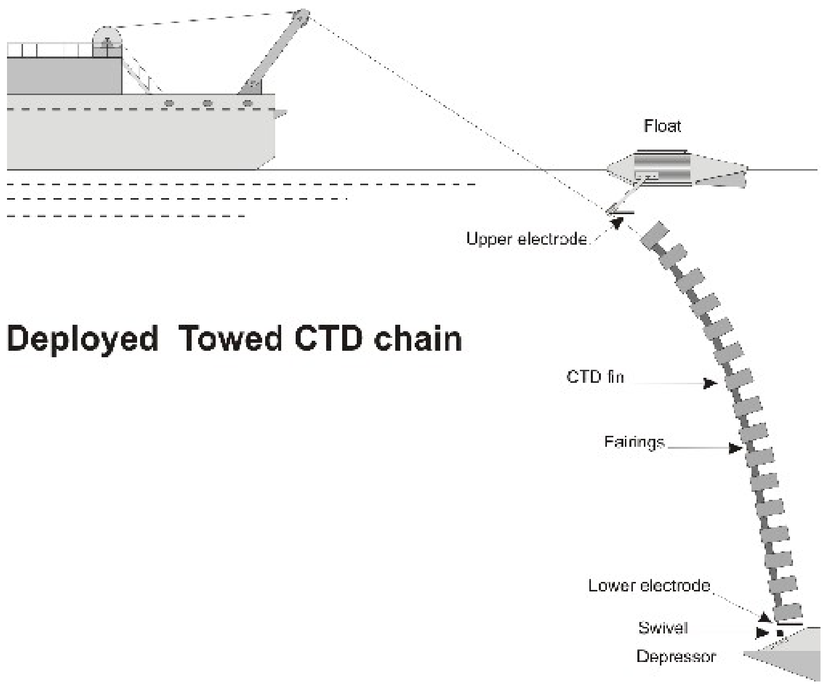


Figure 8. Notional diagram of towed CTD chain (TCTD), reproduced from website of ASD Sensortechnik.

Table 1. Percentages of responding TCTD sensor fins in various NPAL tests/situations.

Date/situation	**Approx max % of responding sensors**
PhilSea09 beginning of tow1	60%
Majority of PhilSea09	25%
Testing DRY on NOAA runway, Nov-Dec 2009	60%
Test in Puget Sound, Jan 2010	40%
PhilSea10 test DRY on reel before first deployment	40%
PhilSea10 beginning of tow1	55%
PhilSea10 beginning of tow2	30%
Majority of PhilSea10 (in both tows)	25-30%

After the instrument's failure of its acceptance test in the PhilSea09 cruise, the months until the PhilSea10 cruise were spent in a series of upgrades and associated tests of the TCTD system. Electronic upgrades in conjunction with the manufacturers, ADM Elektronik, included: a replacement deck unit provided by ADM which allowed for increased power (via increased current) to be sent down the sea cable, frequency changes

in the cable signal (earlier work on the previous deck unit had similarly allowed such frequency changes), new USB interface circuitry aiming to interface with a Windows rather than DOS computer, and new acquisition software. In Nov-Dec 2009, field tests were conducted with this new electronic hardware and software, with the sea cable laid out dry on a NOAA runway to avoid the strong inductive load seen in previous tests on looped sea cable. Meanwhile APL was developing a new armored towline, deployment block, and stronger upper termination to address the mechanical problems in which stresses and impacts on the upper termination had continually disconnected and also damaged the sea cable in PhilSea09. In Jan 2010 an end-to-end electrical test of all the new apparatus (minus the powered reel) was conducted on APL's *R/V Robertson* in Puget Sound. A meticulous meter-by-meter check of cable-jacket integrity was done via electrical insulation tester as the cable was gradually deployed into the salt water, and remaining unseen cable faults from 2009 cruise were repaired. The hardware and software updates described above were tried again on Puget Sound as well. Table 1 lists system performance via approximate percentage of responding sensor fins in the various tests and cruises. Best performance dry or in water still has only about 60% of sensor fins responding, and in situ this number rapidly dwindle with seawater gradually entering the cable (which appears unavoidable when using the cable currently specified by the TCTD manufacturer). Signal timing and signal degradation troubles have been documented by APL as well though, and overall it is still not understood by APL or the manufacturer what causes the remaining 40% of fins to not respond even under the most ideal conditions (e.g. dry and laid out straight), or how the system can be made more electrically robust to small micro-leaks in the sea cable.

NEW RESULTS

It is unfortunate that acoustic data from the DVLA will not be available until Summer of 2011, but there are still some interesting results from PhilSea10 that can be presented now. As mentioned above, the APL cruise included an extensive CTD survey with conventional CTDs. The survey included 51 CTD casts spaced every 10 km from a location near the DVLA to the site where the 55-hour acoustic transmissions took place. Most of the casts were to 1500 m, but every fifth cast was to full ocean depth. Figure 9 presents a map of the computed sound speed along this 500 km track with the mean sound speed removed. This figure clearly indicates exceptionally strong range dependence in the sound speed structure. Apparently a front between two eddy regions lies across this path. Additional strong variability exists between the ranges of 200 and 500 km.

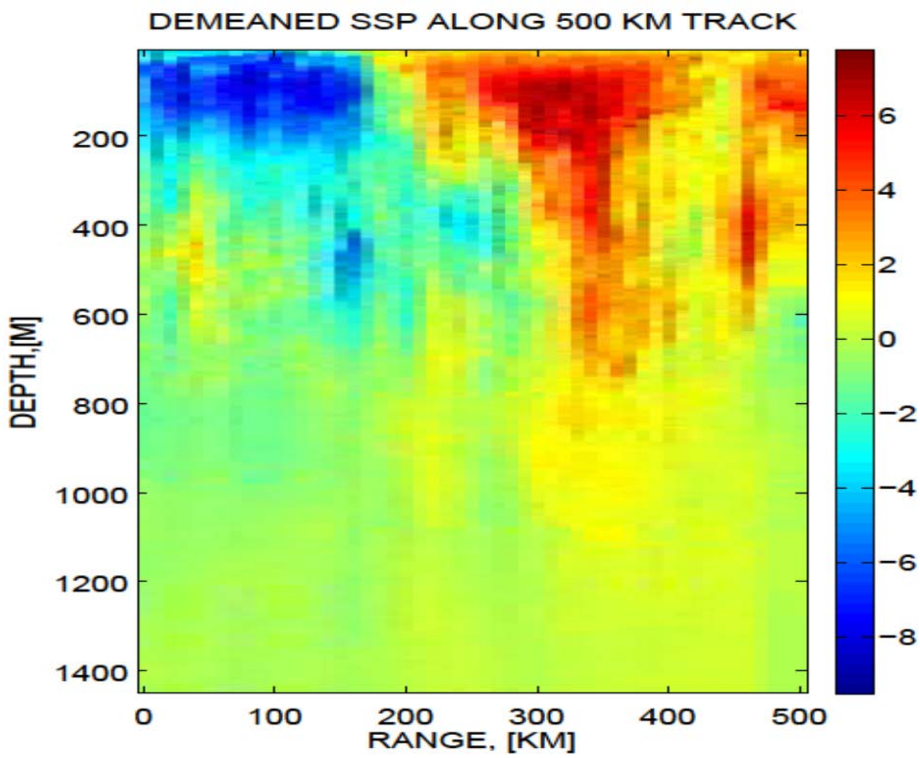


Figure 9. Demeaned sound speed computed from 51 CTD casts along a 500 km path in PhilSea10.

As described above, the performance of the Towed CTD Chain was disappointing, however some data were in fact obtained in the PhilSea10 experiment, and analysis regarding variations via internal waves and spice has commenced on this data. A few preliminary plots of the data are shown below. Two tows of the TCTD were performed and roughly overlapped each other, separated by eight days during which a sequence of CTD casts were also made along the same track (and beyond). The tow region was in approximately the southeast 100km of the path between the DVLA and SS500 (see Fig. 10).

Measurements at sampling periods of 3-5s were obtained during these two tows, with one to three dozen sensors distributed over 700m depth. The first tow was 93km for about 39 hours and the second tow was 124km for about 30 hours. The pressure data was augmented by one or two Seabird CTDs mounted on the TCTD sea cable (one at cable bottom in tow #1, and additionally one mid-cable in tow #2). Preliminary processing showed significant sound-speed structure in the data, as for example in Fig. 11 which shows interpolated anomalies from the background mean sound speed in tow #2.

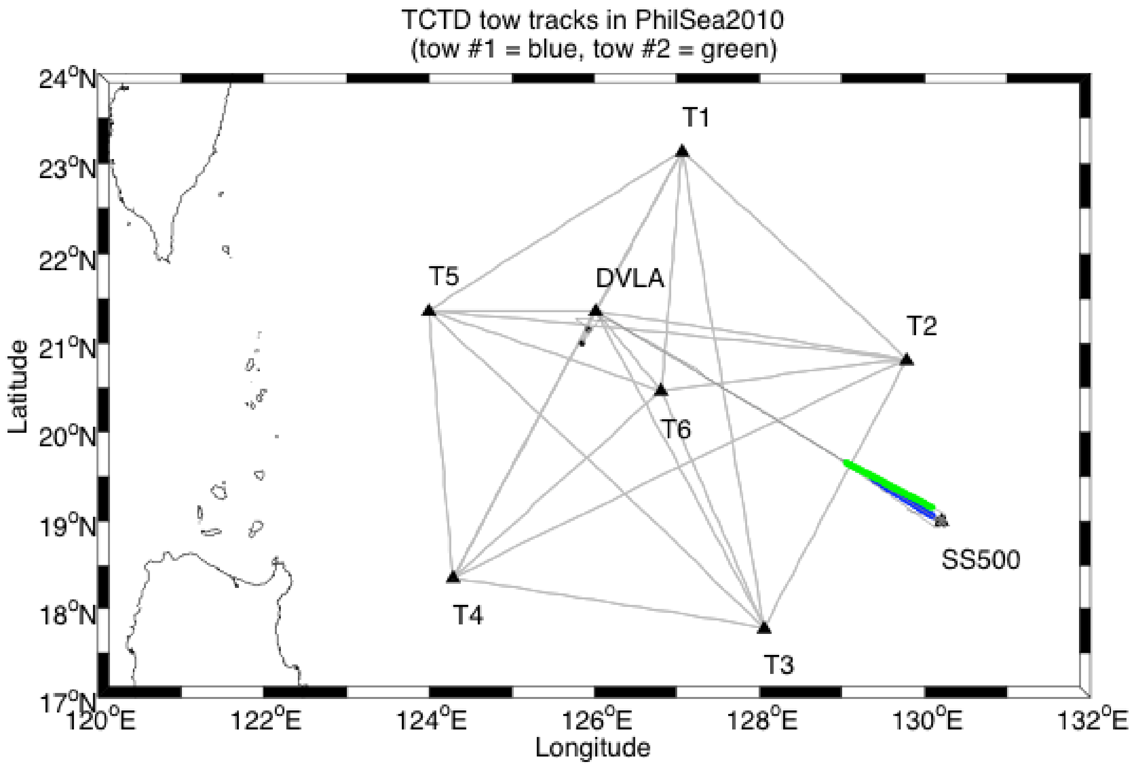


Figure 10. Path locations of the two TCTD tows during the PhilSea10 experiment.

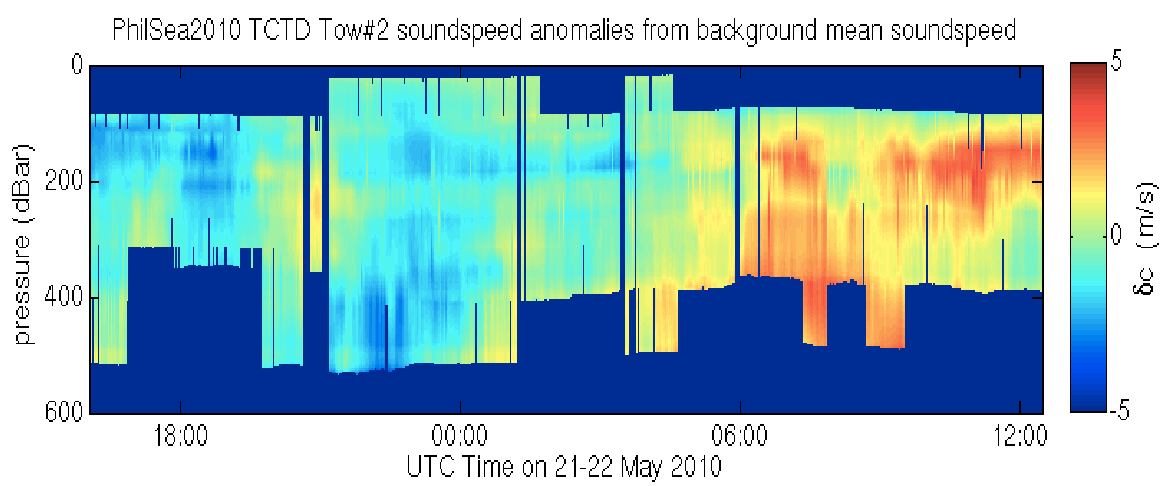
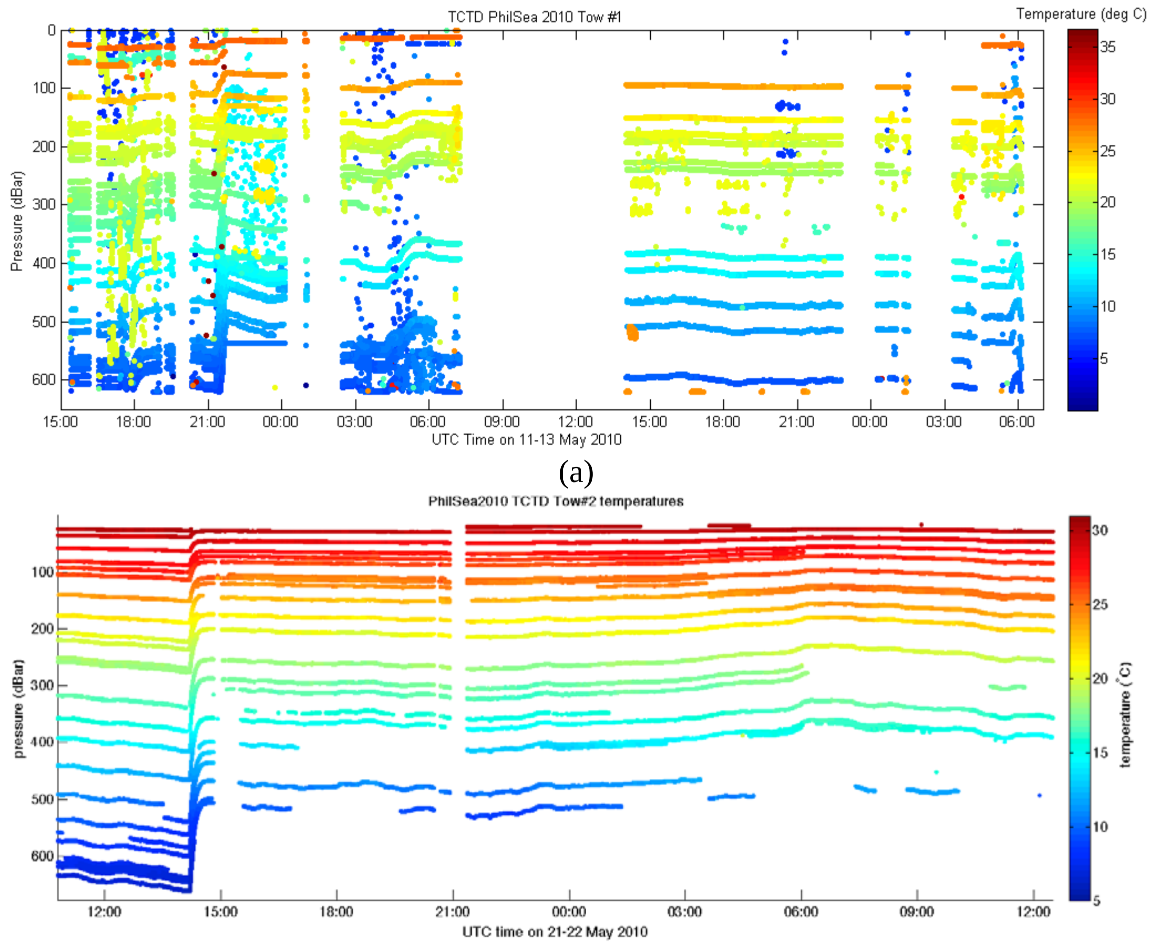


Figure 11. Preliminary plot of interpolated anomalies from background mean sound speed in PhilSea10 TCTD tow #2.

Analysis has only just begun on the PhilSea10 data, but the data coverage for each of the tows can be expressed as in Fig. 12. That figure shows temperature data in colors for each sensor in its path through depth and time. Temperature is shown because it was the

most reliable sensor. Tow #1 has not yet been rigorously cleaned due to complications from numerous non-flagged diagnostic power-data samples that were interspersed with the environmental data bytes (these were turned off in tow #2 after seeing the effort in separating them).



(a)

(b)

Figure 12. Data coverage for PhilSea10 TCTD tow #1 (a) and tow #2 (b). Temperature data is shown because it was the most reliable sensor. Tow #1 has not yet been rigorously cleaned due to complications from numerous non-flagged diagnostic power-data samples that were interspersed with the environmental data bytes.

Another new result from PhilSea10 was the use of dual, or two-color, acoustic transmissions from the MP source. Since the MP transducer has two resonance frequencies, and since the device is more-or-less linear, one should be able to construct a drive signal containing the superposition of a signal with a carrier at the lower resonance and a second signal with a carrier at the upper resonance.

In order to build a composite “dual frequency" drive signal that would be compatible with the transmitter software, the two signals were required to be of equal length over a single signal period. This was simply accomplished by setting one carrier at 200 Hz and the other at 300 Hz, and adjusting the signal Q's to have a 2:3 ratio. This latter adjustment directly defines the number of carrier periods per chip in the respective m-sequences.

Such “two-frequency" signals have been used before in long-range ocean acoustics in the AST experiment, which used carriers around 28 and 84 Hz. Two-frequency signals have also been used in WPRM measurements of the atmosphere, where they are sometimes called “two-color" or even “bi-chromatic" signals.

The two m-sequences in the drive signal are simply summed, so the laws for the two signals were chosen to be different. This allows the time fronts of the two signals to be measured independently. One advantage of this scheme, as shown below, is that a mediocre response for one of the m-sequences need not interfere with a good response for the other m-sequence. One gets two signals for the price of one!

This “bi-chromatic" signal was designed with the parameters shown in Table 2. Adopting the “two-color” nomenclature from atmospheric WPRM, the two components are labeled “red” and “violet”. There are 175.95 pulses per hour for either component, and no pre-equalization was used on the basic signal. A custom C program `makedualmseq` was written to generate the signal file. A section of the raw waveform is shown in Fig. 13.

Parameter		Red signal		Violet signal
Carrier		200 Hz		300 Hz
Law		2033		3471
Sequence length		1023		1023
cycles/digit		4		6
Digit length		20.00 ms		20.00 ms
Bandwidth		50.00 Hz		50.00 Hz
Sequence period		20.46 s		20.46 s

Table 2. **Parameters of the two component m-sequences in the experimental “bi-chromatic” MP200 signal.**

Autospectra for the drive signal and the monitor channel signal are shown in Fig. 14. The sharp response of the MP transducer near 210 Hz clearly provides unfavorable “sharpening” of the “red” component spectrum.

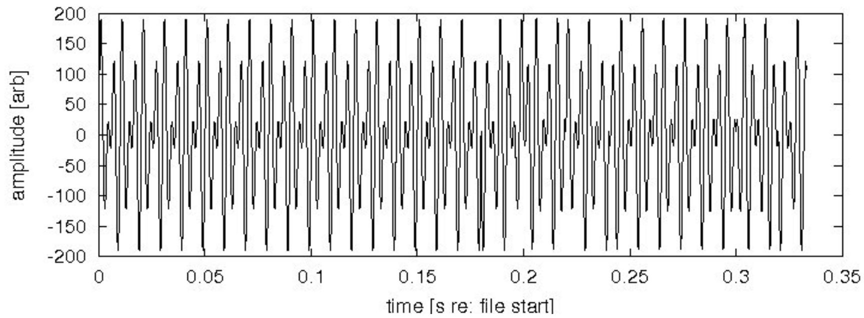


Figure 13. Dual m-sequence signal raw waveform.

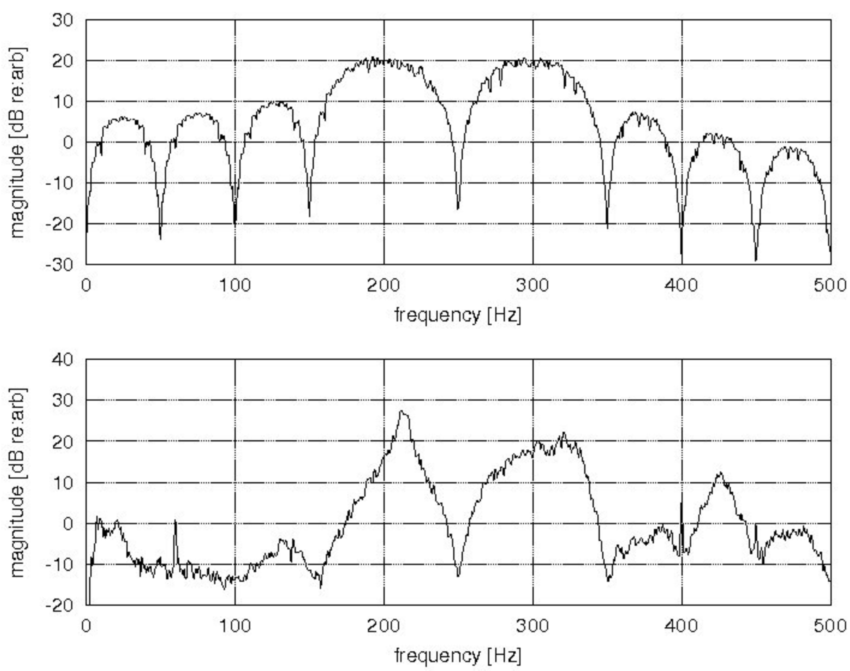


Fig. 14 Dual m-sequence autospectra. Top panel: drive signal, estimated from the drive waveform file. Bottom panel: monitor hydrophone signal, estimated from 30s of data.

Pulse compressed waveforms for both the drive and monitor hydrophone channels are shown in Fig. 15. The pulse response of the violet component is comparable to that in the drive signal --- this can be inferred from Fig. 14 because the spectral shape around 300 Hz in the radiated spectrum has a shape comparable to that in the drive signal. The pulse

response of the red component is considerably broadened compared to that in the drive signal, and this can also be inferred from Fig. 14 because the spectral shape around 200 Hz in the radiated spectrum is much narrower than that in the drive signal.

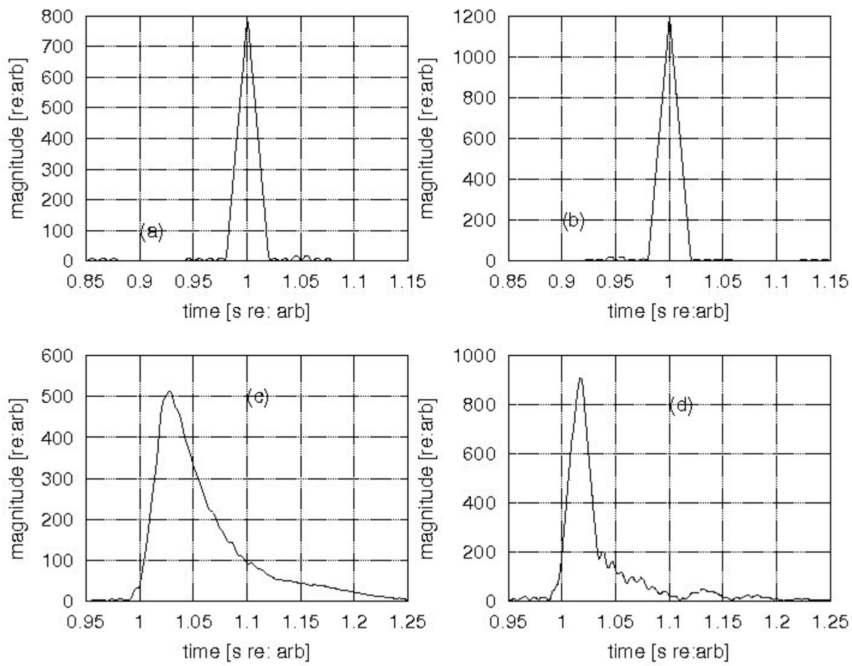


Fig. 15. Dual m-sequence pulses after pulse compression. Panel (a): red component, drive signal. Panel (b): violet component, drive signal. Panel(c): red component, radiated signal. Panel (d): violet component, radiated signal.

These results suggest that post-processing for the MP source signal may be required to equalize the spectral shaping induced by the transducer to improve the timing resolution and/or decrease the trailing side-lobe energy in the "red" component, and perhaps in the "violet" component as well. Future work will investigate whether or not post-equalization is worthwhile.

GRADUATE STUDENT GRANT (N00014-08-1-0200)

Mr. White has made excellent progress toward his Ph. D. degree and is making significant contributions to the NPAL program. Mr. White collaborated in an analysis of the PhilSea09 CTD cast data taken during both the Scripps deployment and recovery cruises, and the APL-UW cruise. This included determination of parameters describing the spatially and temporally-averaged buoyancy frequency and sound-speed. In addition, the perturbations were filtered and contributions from spice and internal waves were separated. The conclusion for PhilSea09 was that there was less evidence of spice in the Philippine Sea than was observed in the north central Pacific Ocean, which was

sampled during LOAPEX [1]. Mr. White also applied fall-rate corrections to the XBT data. This work was presented at the 2009 NPAL Workshop [14].

Mr. White wrote an internal-wave-based sound speed perturbation generator and integrated it into his PE code in order to be able to do Monte Carlo PE simulations. He modeled the Philippine Sea environment using the buoyancy frequency and sound speed profiles mentioned above, adding Garrett-Munk internal wave perturbations. He then completed Monte Carlo PE simulations of broadband acoustic propagation of a 75-Hz signal through the modeled Philippine Sea environment. He presented this work at the October 2009 ASA Conference [15]. Some relevant predictions was the scintillation index for 75 Hz signals along various paths. Mr. White also performed convergence tests with the PE code in order to determine the appropriate range step and number of internal wave modes to be included in GM oceans for 284 Hz center frequency acoustic simulations.

We required an estimate of amplitude fluctuations due to changes of the receiver position in the acoustic field. The ray method provides an accurate prediction of deterministic amplitude at positions sufficiently removed from caustics. Mr. White computed eigenrays to all tracked upper array hydrophone positions relative to each of the two APL-UW source deployment ranges during the month-long deployment of the DVLA. He then made an estimate of the scintillation index due to changes in receiver position for the two source deployment ranges.

The transfer function of the MP acoustic projector consisted of two sharp peaks at frequencies of 210 and 320 Hz. Since the ideal transfer function would be “flat” across these two frequencies, the M-sequence waveform was “pre-equalized” [9]. The pre-equalization filter was not expected to be optimal for full-power at-sea operation, and substantial ringing in the pulse-compressed signal recorded on both the monitor hydrophone and the 45 km distant Scripps DVLA was observed. Dr. Rex Andrew (APL-UW) therefore designed a filter to “clean up” the recorded signal prior to pulse-compression. Mr. White applied this filter to acoustic receptions made on the Scripps DVLA. When Mr. White plotted the reception on all hydrophones of a single acoustic pulse, we noticed that the signal seemed to arrive at different times for each hydrophone. This caused the time front to appear ragged. Apparently the sample rate of each hydrophone, which is set by its internal oscillator, can be slightly different than its nominal value of 1953.125 Hz [16]. He corrected this error in a rough fashion by skipping to the sample nearest the actual transmission time at the start of each transmission. For the long-duration transmissions, this method results in an error of less than one sample over the duration of the transmission. For the worst-case clock-rate error, the effect on the amplitude estimate was negligible. The results of this clock correction are shown in Figure 16.

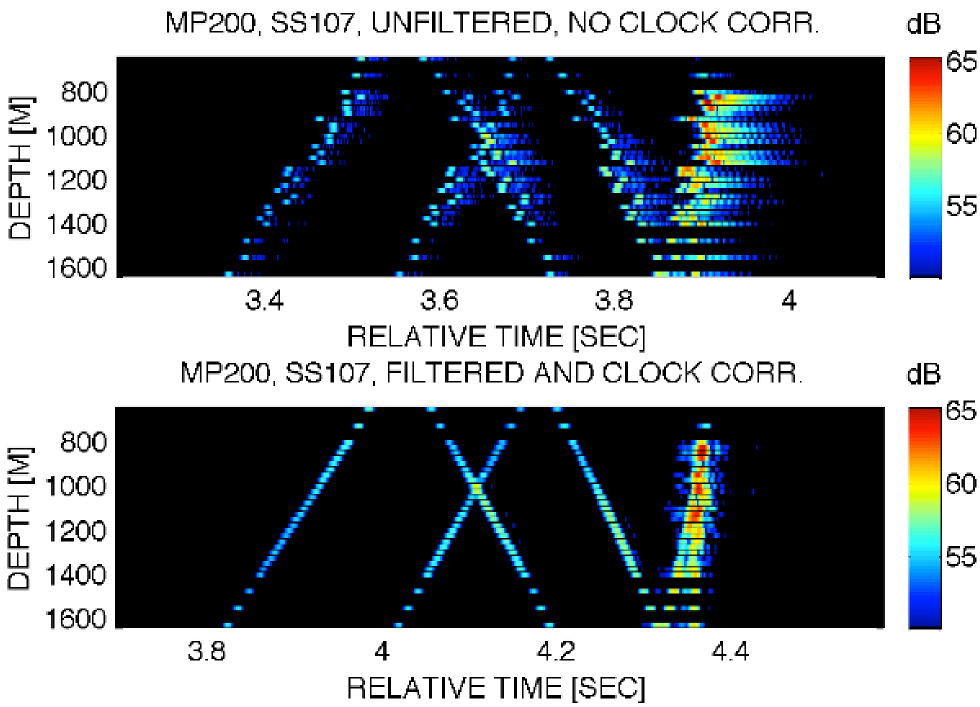


Figure 16. An example timefront from SS107 before and after clock corrections and filter are applied to data.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

RELATED PROJECTS AND COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW),

V. Ostashev (NOAA/ETL), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D'Spain who is funded by the signal processing code of ONR.

In addition to supporting the APL-UW cruise in PhilSea10, Rex Andrew participated in the SIO cruise led by Peter Worcester.

Immediately after the SIO cruise, APL-UW transmitted the CTD casts made during the cruise to Terry Rago of NPS, who graciously processed and re-formatted the data into R-T messages, which he then sent on to NAVOCEANO.

We supplied Dr. Tarun Chandrayadula (currently a National Research Council Post-Doctoral Fellow working with Prof. J. A. Colosi at the Naval Postgraduate School) with both transmission diagnostic files from the APL/UW transmitter and acoustic hydrophone receiver files from the Scripps deep and shallow vertical line arrays from multiple stations in the 2004 LOAPEX experiment.

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APL - North Pacific Acoustic Laboratory

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.

2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. The North Pacific Ambient Noise Laboratory, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consists of the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the locations of acoustic hydrophone arrays in the Laboratory and major shipping lanes.

The second avenue includes highly focused, comparatively short-term experiments. We have recently completed an experiment in the Philippine Sea called PhilSea10 [1]. See Figure 2. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the DVLA from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT). Analysis of environmental data from PhilSea10 is underway, and we recently received the acoustic data from the Distributed Vertical Line Array (DVLA).

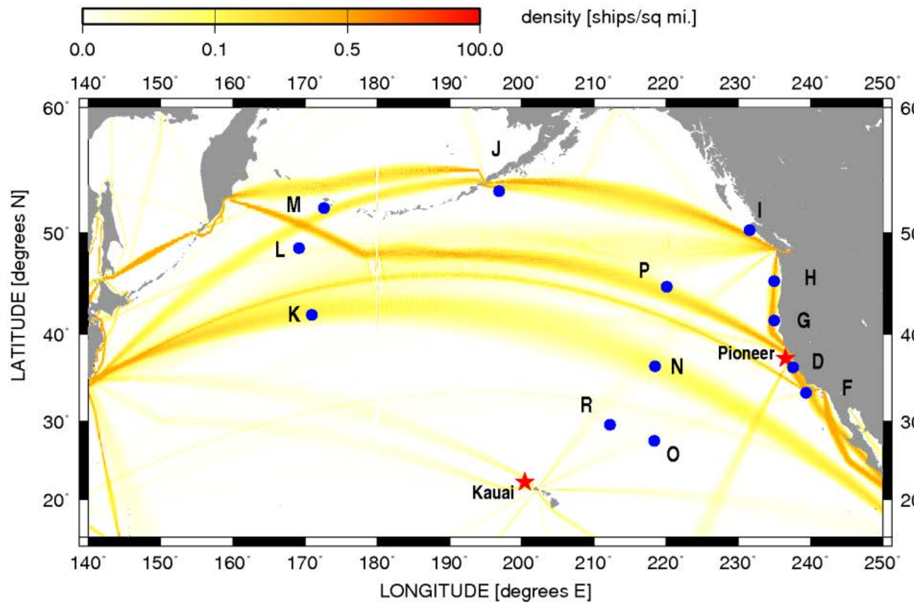

Figure 1. "The North Pacific Ambient Noise Laboratory". The blue circles are receivers: locations D, F and R are exact. All other receiver locations are notional. The red stars indicate transmitters installed under the ATOC program. The color mapping utilizes the "merchant" shipping density from the HITS 4.0 shipping density data base [2]. Note the nonlinear density color scaling.

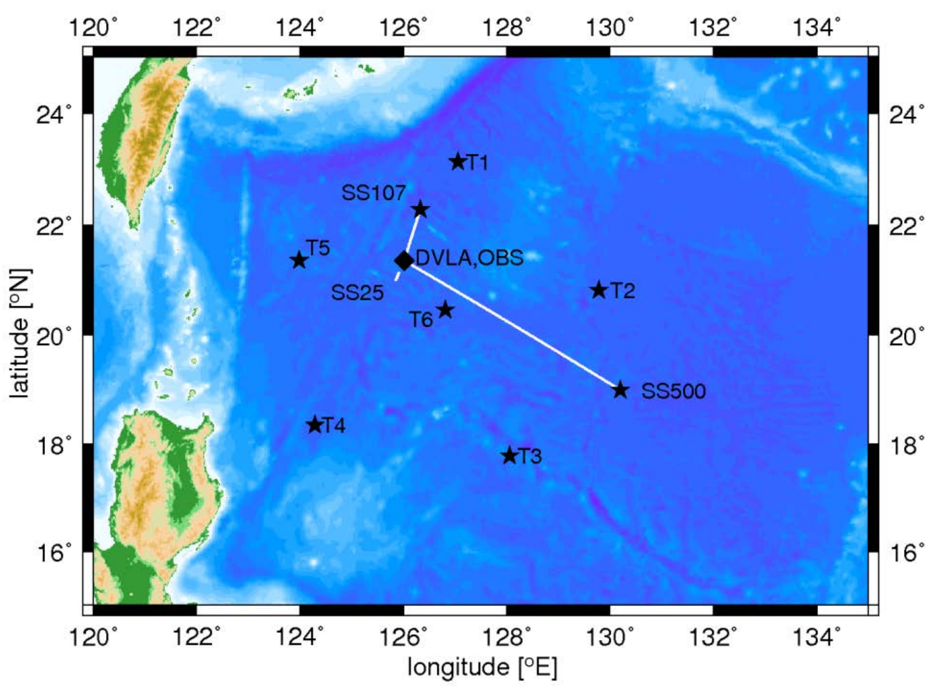

Figure 2. Major elements of PhilSea10

WORK COMPLETED

North Pacific Ambient Noise Laboratory-

Our recent *JASA* paper [3] reports a significant decrease in ambient noise levels at two northern sites where we have been measuring ambient noise levels for more than a decade. A figure from this paper is presented here as Figure 3.

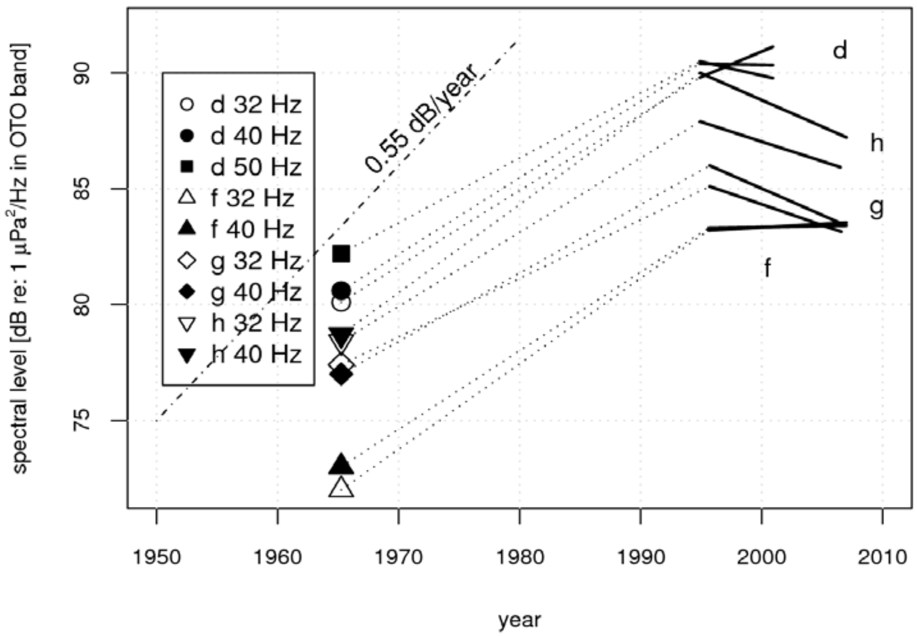

Figure 3. Long-term trends in ambient noise

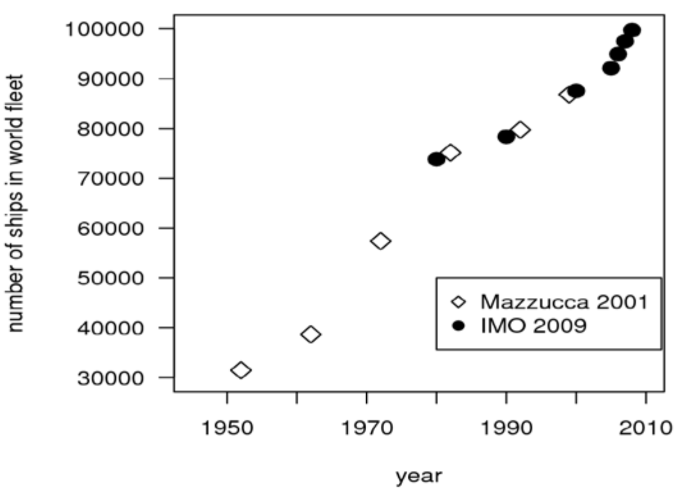

Figure 4. Number of ships in the world fleet.

Ten years ago, we were working with Lori Mazzucca, a graduate student in the University of Washington School of Marine Affairs, and she published [4] some statistics on the size of the world's merchant shipping fleet. Her statistics were deduced from databases such as Lloyd's of London. Her results are shown in Figure 4. Up through 1982, the values she reported came from a book [5]: The values from 1992 and 1998 came from a personal communication [6] with an investigator who apparently had access to Lloyd's or a similar database and reduced the data to these statistics. Of course, the period 1995 and later encompasses our APL-UW time series so it remained of interest to update Mazzucca's figure.

This year, we located additional reduced statistics published on the Internet by the International Maritime Organization (IMO) [7]. They provide values for 1980, 1990 and 2000, and then 2005-2008. These are also plotted in Figure 4. The IMO numbers for 1980, 1990 and 2000 correspond very well with those from Mazzucca (which involved two sources.) This gives us confidence that these IMO values were derived from similar original data sources in similar ways. It follows that the IMO numbers for 2005 to 2008 provide a quantifiable indication of the world merchant shipping fleet over the rest of the period of the APL-UW dataset.

On another subject, M. Ainslie of The Netherlands Organization has questioned whether the levels we reported in [3] represent the average ambient noise level. He presented a theoretical calculation [8] that indicated that the increase in worldwide noise levels is explained by the increase in the number of ships, notwithstanding our recent result. In further discussions, Ainslie explained that his calculation produces an “average noise power” $<|p|^2>$, whereas we report a median level.

These two quantities are not the same. As we explained in [9], the median measure is insensitive to sporadic extra-loud events in the noise record. This was desirable because we were comparing statistics from our data set with those generated by Wenz for the 1960s; and Wenz used a semi-manual editing procedure to eliminate time data segments containing extra-loud events. It was Wenz's rationale that the extra-loud events were due to individual ships passing close by the receiver, and he was interested in characterizing the “distant shipping”, i.e., a measure not biased by these sporadic extra-loud events.

Our hypothesis is that the noise level (on, say, daily timescales) due to distant shipping fluctuates moment-by-moment by only a minor amount about a time-averaged “mean” level. We call this process the “background”. A population of short-time background noise measures should be well-described by a Gaussian distribution, and, when this is true, the median will be the same as the mean. Sporadic loud events cause a heavy upper tail in the distribution; the mean of such a dataset would be higher than the median level.

Philippine Sea-

Spatial statistics of internal waves and ocean "spice" (density-compensated sound-speed fluctuations) are important for modeling their effects on ocean acoustic propagation. Previous work has investigated the vertical distribution of spice in experiments, but not the horizontal, and the aspect ratio of these phenomena are crucial for the acoustic modeling. Intermittency and the fact that the spice features are of the same scale size as collocated internal waves complicate the picture. Empirical investigation of these phenomena are key to improved modeling.

An 800 m version of the "towed CTD chain" (TCTD) instrument [10] was used in the Philippine Sea 2010 experiment to attempt to measure temperatures and conductivities in a 2D ocean slice along towpaths of order 100km (see Figure 5). These were to be densely sampled measurements in space and time, from which horizontal strain spectra could be computed along long horizontal paths interpolated amidst the dense samples, at each of many depths. Thus the depth-dependent nature of the horizontal spice statistics could be analyzed in that experiment. Unfortunately the instrument performed poorly, producing only a small subset of useable data in the tows, but we do have some data to work with and we have been proceeding with a modified version of the planned analysis by supplementing the limited TCTD data with the sequence of CTD casts taken nearby in space and time to the analyzed TCTD tow (Figure 6).

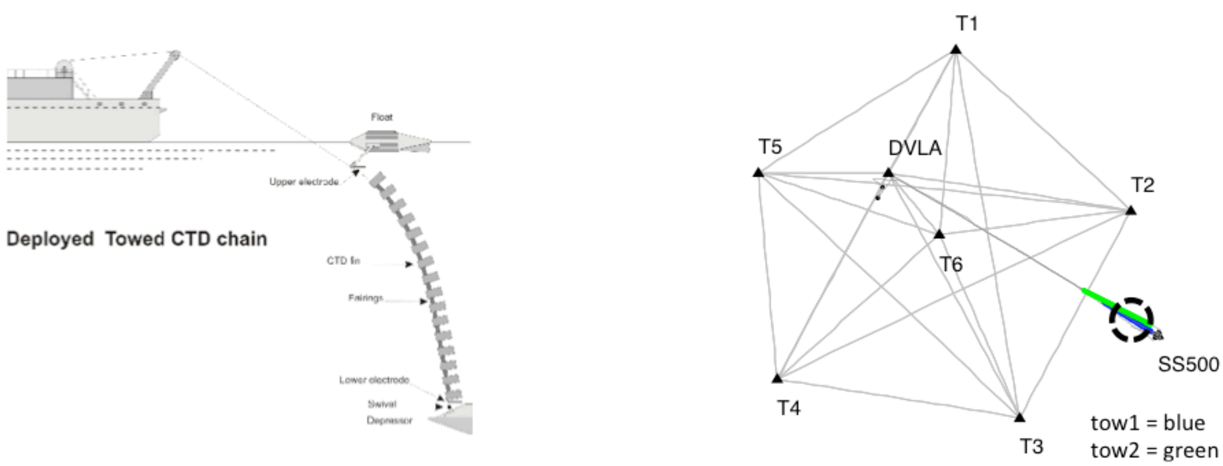

Figure 5. Left: experiment configuration; a 800 m sea cable with 88 CTD sensors is towed behind the ship, with the help of a float and a depressor. Right: experiment geometry; the two TCTD tows were within the 100 km west of ship stop SS500. Tow #2 had better data quality and has been the focus of the analysis.

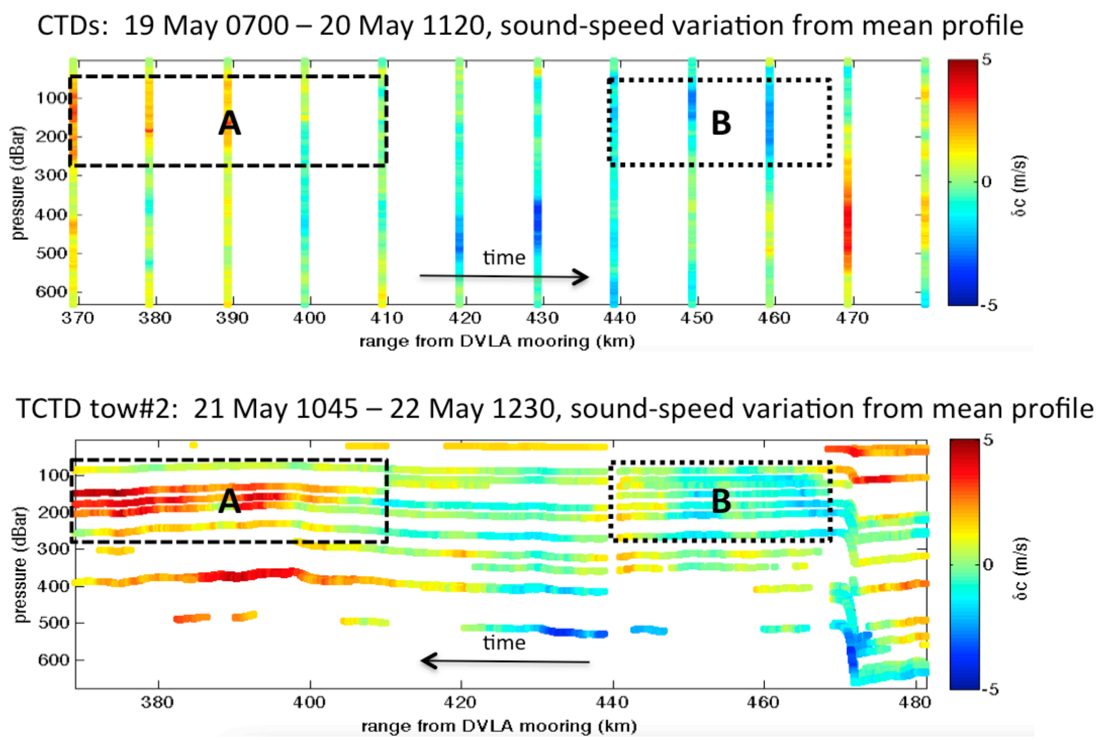

Figure 6. Top: soundspeed anomalies in CTD casts along the TCTD tow track. Bottom: soundspeed anomalies in TCTD tow#2. The mean profile subtracted in both plots is that of the 12 CTD profiles shown.

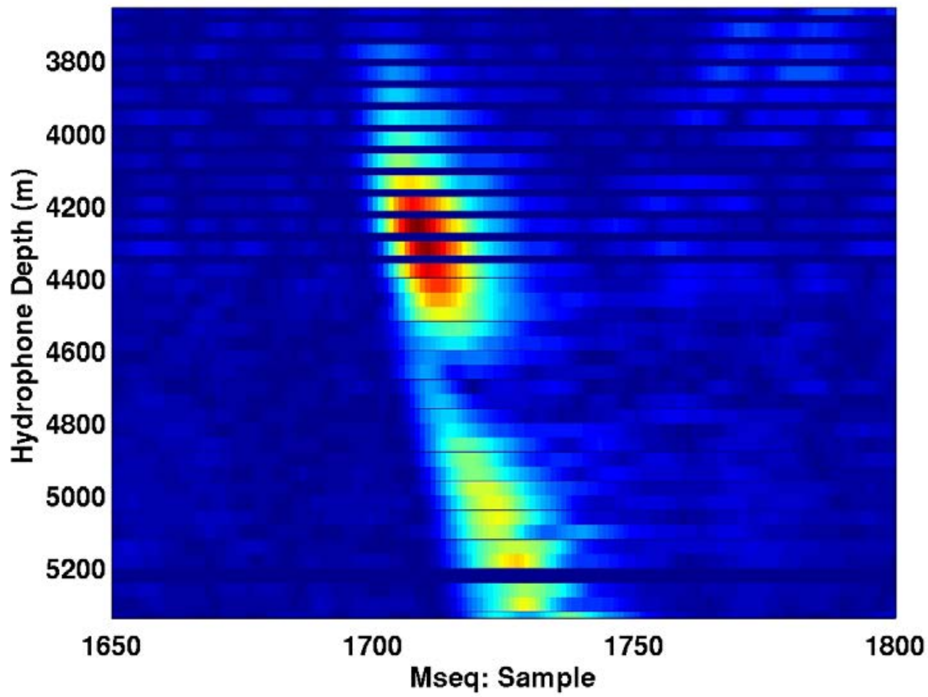

Figure 7. DVLA reception from the 150 depth source drift at 25 km range.

The first DVLA acoustic data to be analyzed from PhilSea10 are from the shallow acoustic source "tow." Figure 7 shows the reception of a single M-sequence on the deep hydrophones of the DVLA. The HX554 source was suspended to a depth of 150 m and continuously transmitted a M-sequence with a carrier frequency of 57 Hz while the ship moved from 25 to 43 km away from the DVLA. The white line labeled SS25 in Figure 2 shows the approximate line of the drift. The "tow" was actually a controlled drift since the ship was moving with the current away from the DVLA and only the bow thruster was used to maintain orientation and the drift path. This was done to limit the ship's radiated noise. The purpose of the exercise was to study the reliable acoustic path (RAP) range and the effect of the bottom on the RAP range. The RAP range was predicted to be approximately 30 km.

We have been using the Navy Standard Parabolic Equation, NSPE 5.4, for the 107 km simulations of PhiSea2009 configurations (SS107 on Figure 2). These Monte Carlo simulations require wall-clock timescales of months. Corresponding 500 km calculations for the PhilSea2010 configuration (SS500 on Figure 2) do not appear feasible with this code on our cluster. We have therefore been investigating an upgrade to our computational capacity.

The simplest option would be to migrate NSPE to a new target cluster, except that NSPE has distribution restrictions that preclude this.

The next option was to migrate the pertinent parts of NSPE to a code base that could be targeted for a new cluster. NSPE implements two parabolic equations: RAM and the SS-Fourier PE. RAM is widely used in our long-range community, so we investigated migrating RAM.

The original Michael Collins RAM is available as open source, i.e., from OALIB. Matt Dzieciuch has ported that code to Matlab, and Brian Dushaw has ported Matt's code back to Fortran. Collins' RAM consists of several features: (1) the “split-step Padé” algorithm, (2) computational tricks to increase speed, and (3) specialized I/O routines. The split-step Padé algorithm is the heart of the code. The computational tricks presume that the sound speed field, the seafloor depth, and/or the bottom composition remain unchanged for many range grid points. This is a good model for many deterministic calculations, but not relevant for what we need. The input sound-speed field for a scattering calculation contains a different sound-speed field at each range step. Most of RAM's computational tricks can therefore be eliminated for our application. This also eliminates the applicability of all specialized I/O routines.

In addition, RAM is a single frequency calculation, whereas our simulations require a time domain result. This suggests that we needed a “broadband” application with embedded split-step Padé engines at each of many frequencies, with a back-end inverse Fourier transform.

We have therefore developed a “modified RAM” suitable for deployment without restrictions to any compute cluster. This code uses Collins' split-step Padé formulation,

but eliminates many of the tricks used in recalculating the implicit finite-difference matrices, and also substitutes a simple and straightforward tri-diagonal solver. Those tricks made RAM fast for a certain class of problems, but most of that gain is not applicable to our scattering problems.

Graduate student Andrew White passed his General Exam in June this year. Most of the year has been dedicated to modeling acoustic propagation of signals transmitted by APL-UW during the pilot study/engineering test PhilSea09.

White's modeling of the environmental variability during PhilSea09 consists of two separate simulations. In the first simulation, approximately 200 independent, Garrett-Munk (GM) internal wave perturbed random oceans were generated, and then the acoustic field from a point-source was propagated through each of these oceans. The purpose of this simulation was to create an ensemble from which to calculate statistics such as the scintillation index (SI) for each of the four arrival groups corresponding to the ray paths shown in Figure 8. This method is commonly referred to as the Monte Carlo Parabolic Equation method in the deep-water acoustics community.

For the second simulation, the internal wave field in one model ocean is evolved in geo-time. The GM spectrum is bounded in temporal frequency by the inertial (32-hour period at this latitude) and buoyancy (10-20 min. period) frequencies. A GM internal wave perturbed ocean is evolved over 10 inertial periods, or about 320 hours, at a time-step of 240 sec. At each time-step the acoustic field from a point-source is propagated to a range of 107 km.

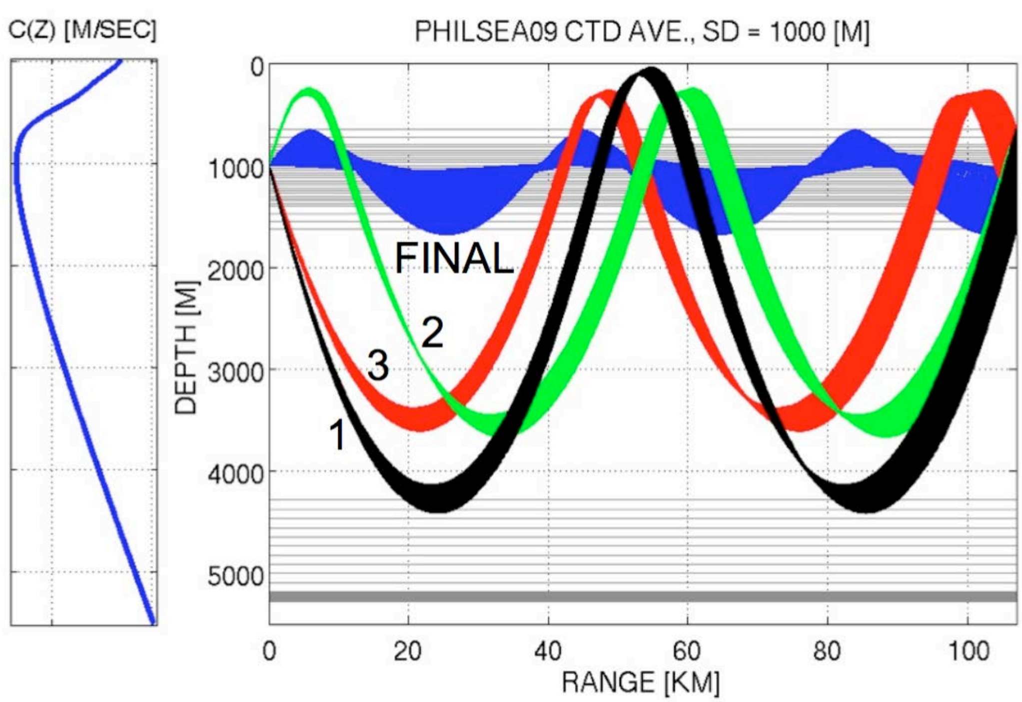

Figure 8: Ray paths of acoustic waves that reach the upper hydrophones at 107 km range.

In Figure 8, ray paths refract according to the sound-speed profile shown at the left of the Figure. Only purely refracted rays which reach the receiving array at 107 km range are plotted. Hydrophone depths are represented by gray lines. Note that the spacing in depth between hydrophones was variable. The gray band near 5 km depth is a group of closely-spaced hydrophones. In this work, receptions on the lower section of hydrophones were not considered. Paths are numbered in the order of their arrival time at the depth span of 1500-1600 m at the receiver for a pulsed source.

NEW RESULTS

North Pacific Ambient Noise Laboratory-

Figure 4 clearly quantified the belief that the number of ships has continued to increase with time. But the trends we see in our acoustical records suggest that the shipping traffic contribution to oceanic ambient noise is decreasing. At first thought, one might think the world fleet size to be a reasonable indicator for oceanic ambient noise, so this new result seems counter-intuitive. More research is required to understand and/or resolve this apparent contradiction.

As mentioned earlier, our oceanic ambient noise statistics are based on medial levels, not the average noise power. These two quantities are not the same. Our hypothesis is that the noise level (on, say, daily timescales) due to distant shipping fluctuates moment-by-moment by only a minor amount about a time-averaged “mean” level. We call this process the “background”. A population of short-time background noise measures should be well-described by a Gaussian distribution, and, when this is true, the median will be the same as the mean. Sporadic loud events cause a heavy upper tail in the distribution; the mean of such a dataset would be higher than the median.

This difference has now been proven with our North Pacific ambient noise datasets. The narrowband noise level distributions for sites D, F and G (see Figure 1) have been shown [3] to have heavy upper tails. We therefore computed the population mean for each one-third octave band across the entire dataset (6 to 12 years of data) for sites D, F and G, and compared them to the population medians. The results for all three sites confirm that the mean measure is 3 to 4 dB higher than the median. This new consistent result suggests that Ainslie's average noise power is related to our distant shipping measure by some transformation that incorporates the frequency and strength of loud events. We are developing a theory to define this transformation.

This issue is of considerable interest to the ASW community, which has long sought a characterization of the frequency and duration of “quiet periods” (which could be considered the complement of loud events), and the ocean acoustic ecology community, which is currently striving to characterize, measure and predict noise exposure in the marine environment.

Philippine Sea-

Ambient noise levels measured during the 2010-2011 Philippine Sea experiment on the Scripps DVLA and reported in [11] show an “unexpected" decrease in level as depth decreased from about 1000m to the surface.

To infer whether or not this kind of ambient noise profile is to be expected, we performed a simulation using the Navy standard “Dynamic Ambient Noise Model” (DANM) in non-dynamic mode. These calculations do not include any scattering mechanisms, and utilize purely “deterministic” monochromatic transmission losses from sea surface sources (ships and wind waves) to selected receiver depths.

The code was executed at the APL-UW NPAL secure processing facility (because the bathymetry database DBDB-V is a classified database.)

Ambient noise levels for depths 50m, 100m, 150m, …....1000 m are shown in Figure 9 for three frequencies: 25Hz, 100Hz and 300Hz. The levels are decibel equivalents for density values, i.e., measured in a 1 Hz band. Further interpretation remains questionable: we believe these predictions are indicative of the contribution from “distant shipping” because the areal integration extends out to a radius of approximately 1000 nm. The calculation does not include any contributions from discrete ships --- which would represent “local shipping”---but the areal integration appears to start at a radius of 0 nm, i.e., overhead. Additionally, it is unclear to what extent the wind-generated surface noise is incorporated into this calculation.

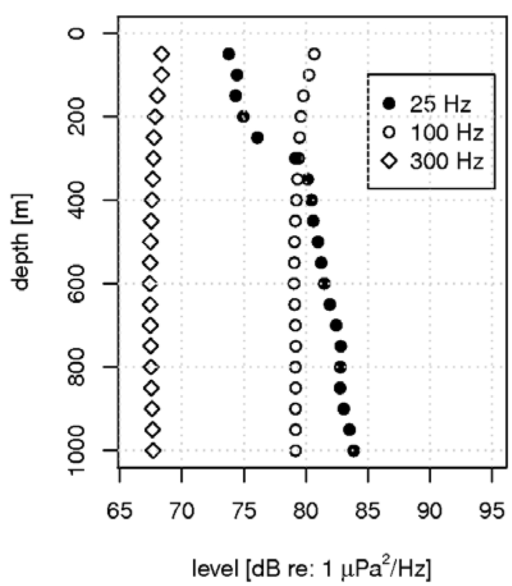

Figure 9. DANM predictions for the vertical noise profile, Philippine Sea experiment.

The profile at 25Hz is likely dominated in the model by distant shipping. (There are no biological contributions in DANM.) This profile does have a decrease of about 10 dB from the deep sound channel axis (approximately 1000 m) to 50 m. We are not sure what sources influence the predictions at 100Hz and 300Hz, but the model suggests these levels are nearly constant across the depths simulated. These results were distributed to collaborators in our community in Reference [12].

The TCTD pressure, temperature, and salinity measurements are used to compute the density-based and sound-speed-based components of vertical displacement, each via the same equation of state [13], according to the methods of Henyey et al. [14]. Other APL work has already focused on studying the vertical variation of spice in the Philippine Sea by similar methods [15]. By definition, these density and sound-speed components of displacement diverge in regions of ocean spice. The analysis here focuses on wave number spectra of horizontal strain, the horizontal derivative of the displacement. The density-based strain spectra are due entirely to internal waves, while the sound-speed-based strain spectra are due to both internal wave and spice components. We expect the sound-speed-based spectra to generally be larger than the density-based ones, the imaginary part of their cross spectra to be zero, and the real part of their cross spectra to be close to the density-based spectra. We can use these theoretically-expected features to check that the data-based results were computed correctly. The difference between the sound-speed-based and density-based spectra then corresponds to the amount of spice present.

In Figure 10 we see regions of spice in the lower part of dataset for box A (see Figure 6) and the middle of dataset box B. All the results for dataset box B, and the results for the lower part of dataset box A, agree with the expected theoretical checks described above. However, the results for the upper part of dataset box A do not – the imaginary part of the cross-spectrum are close to zero, but the density-based strain spectrum is larger than the sound-speed-based one, and the real part of the cross-spectrum follows the sound-speed-based spectrum rather than the density-based one (e.g. at 140m in dataset A, also seen in other results not shown for dataset box A). This is contrary to the theory. Yet the code is successful in computing results which pass these theoretical checks in all the vertical CTD cases, and a number of other horizontal TCTD cases. And when the same analysis is instead run on simulated data generated from a Garrett-Munk internal wave displacement spectrum [16], the density-based and sound-speed-based spectra are identical because there is no explicitly separate spice in that simulated data. This all suggests that this discrepancy between measured results and theory may concern how we handle features in the data as opposed to troubles in the code itself:

The displacement quantities from which the strains are computed are based on the non-adiabatic components of the density and sound speed and their vertical derivatives. The towed chain data has problems with vertical gaps, so not only must we vertically interpolate TCTD sensor data, we also use smoothed averages of our conventional CTD casts as a background field to provide the adiabatic density and sound speed components and the vertical derivatives. Presently our calculations use range-independent smoothed averages of the CTD casts for this background field, but it may be necessary to use a

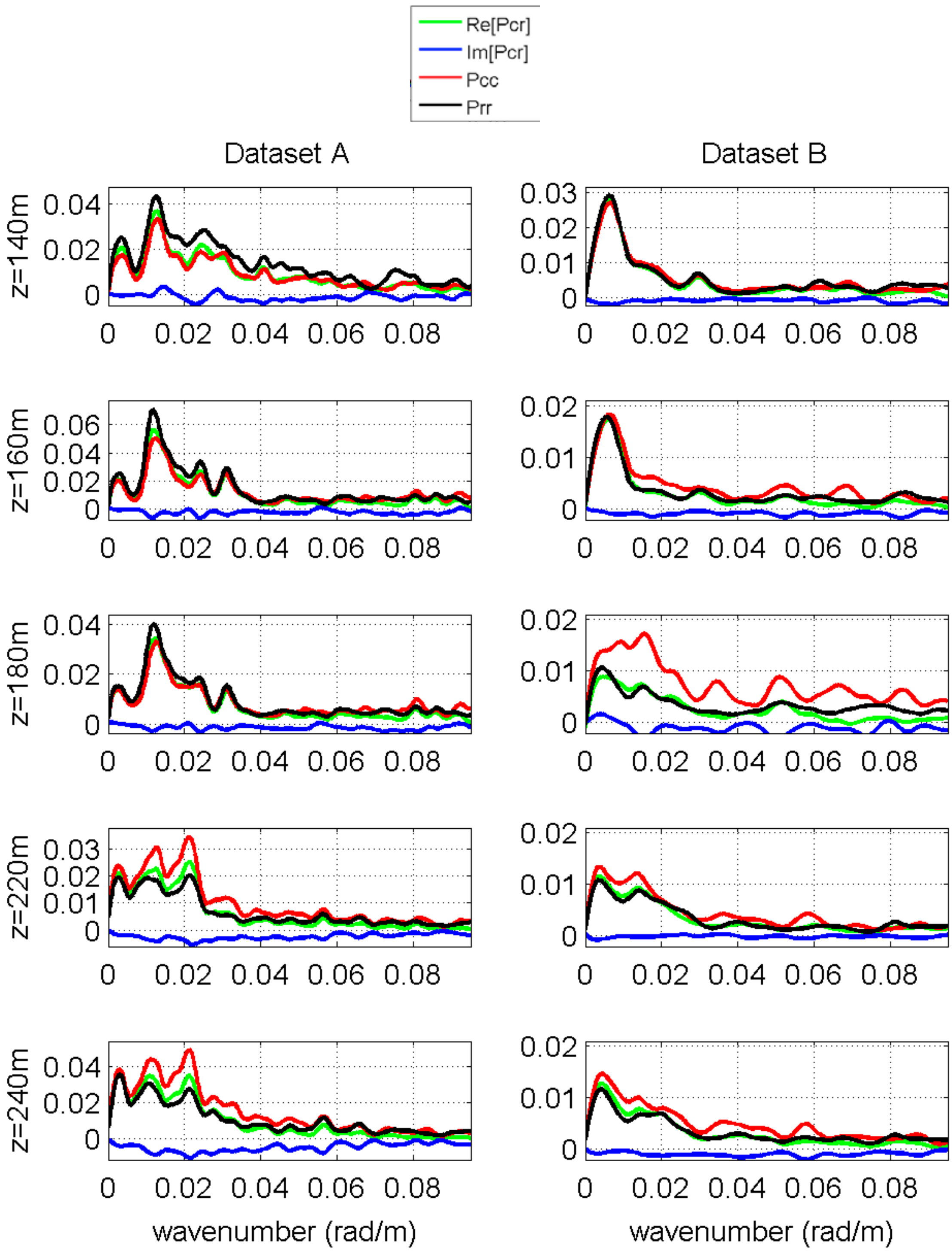

Figure 10. Spatial spectra of horizontal gradients in displacement (i.e. horizontal strain), at depths 140-240m, along the sub-segment of TCTD tow #2 shown in Fig. 2. The same depths were used for both datasets A and B. Prr is the power spectral density of the density-based strain, Pcc is that of the sound-speed-based strain; the other two lines are the real and imaginary parts of their cross-spectral density Pcr.

range-dependent smooth background instead. Also we note the timing of the CTD and TCTD data collection – the ship acquired CTD casts in the direction of increasing range from the DVLA, then turned around and took the TCTD data in the opposite direction, so the right sides of the two plots in Figure 6 are closest together in time. This means that the background field for dataset B was computed from data that was closer in time to its corresponding TCTD data than was the case for dataset A. We are presently exploring these possibilities in hopes of explaining this discrepancy between measurement results and theory in dataset A.

The end interest in these investigations is toward improvement in acoustic propagation modeling and understanding, ultimately looking to questions like, "Is it beneficial to bring a TCTD along in long-range ocean acoustic experiments in the future? Must one aim to obtain a fully-sampled (in time and space) dataset for direct use in propagation modeling, or could a spectral description suffice?" Unlike for linear internal waves, a spectral description of the distribution of spice is not a full description of its distribution – spice is a greatly intermittent and non-Gaussian process, with "blobs" here and there. In focusing this work on spectral descriptions of spice, we acknowledge that it is an initial step toward the understanding of this phenomenon, but not a complete enough description to fully model spice distributions directly from the spectra. The benefits will depend on application – tomographers typically focus on travel-time variations, which are chiefly affected by low-wavenumber variability in the sound-speed field. But phenomena like scattering and deep-fades manifest themselves more in intensity variations, which are chiefly due to higher-wavenumber variations in the sound-speed field. If successful, the spectral results in this work would provide an empirical view into the horizontal scales of variability of both internal waves and spice in the ocean.

As mentioned in the Work Completed section, in the second simulation, the internal wave field in one model ocean is evolved in geo-time. The GM spectrum is bounded in temporal frequency by the inertial (32-hour period at this latitude) and buoyancy (10-20 min. period) frequencies. A GM internal wave perturbed ocean is evolved over about 10 inertial periods, or 320 hours, at a time-step of 240 sec. At each time-step the acoustic field from a point-source is propagated to a range of 107 km for eventual comparison with the actual data collected during PhilSea09.

A simulated time series (see Figure 11) for acoustic intensity is formed in this manner and correlation functions and spectra will be computed from this time series for each of the four arrivals. The purpose of this simulation is to form predictions for time-dependent statistics. Figure 12 presents the actual time series of APL-UW signal receptions recorded on Scripps' hydrophone array during PhilSea09. These receptions correspond to the modeled receptions shown in Figure 11. The y-axis is intensity in decibels, with an offset applied for visualization. Notice the long-period variability observed in arrival one which is not modeled by the GM internal wave perturbed simulation. The GM model characterizes a large amount of oceanographic data, and has been seen to generally agree with observations in the deep ocean and at geographic locations sufficiently removed from strong sources of internal waves. There have been, however, exceptions to this rule. The parabolic equation model contains all of the relevant physics, so if the hypothesis is

incorrect, the GM model's (or the values used as its parameters') applicability in this region will fall into question. Though this would be a negative result, that result would be significant –as the Monte Carlo method involving the GM spectrum of internal waves is generally assumed to work when more efficient analytic approaches cannot be applied. Obviously, the next major step is to compute the relevant statistics for a detailed comparison.

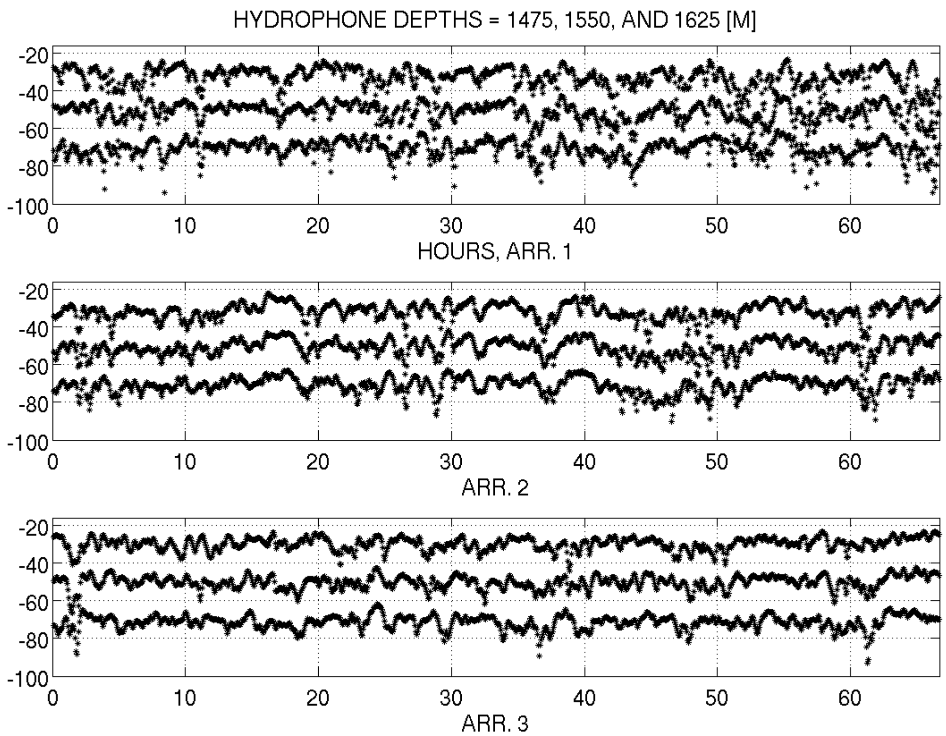

Figure 11. Example time series from the geo-time evolved internal wave ocean simulation. Shown in the top panel are the modeled receptions of ray path arrival one recorded on three adjacent hydrophones, at 1475, 1550, and 1625 meters depth. The y-axis is the relative intensity in decibels, with an offset applied for visualization; source level is not taken into account. Panels two and three show ray path arrivals two and three. All three paths correspond to those depicted in Figure 8.

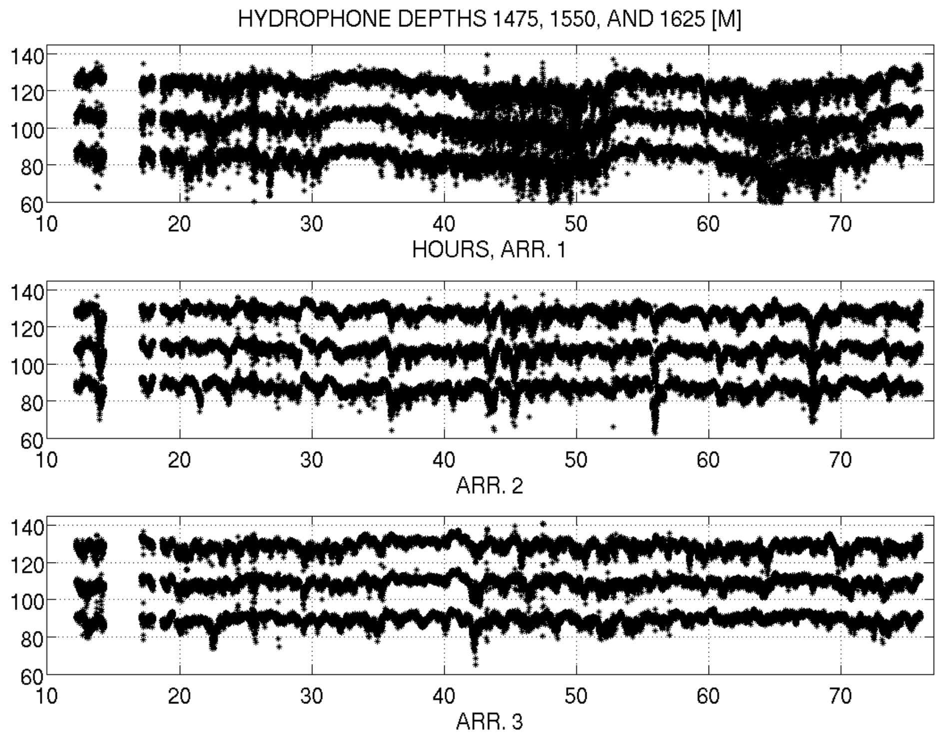

Figure 12. Actual time-series of APL-UW signal receptions recorded on Scripps' hydrophone array during PhilSea09. These receptions correspond to the modeled receptions shown in Figure 11. The y-axis is intensity in decibels, with an offset applied for visualization. Notice the long-period variability observed in arrival one which is not modeled by the GM internal wave perturbed simulation.

RELATED PROJECTS AND COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D'Spain who is funded by the signal processing code of ONR.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate

that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

TRANSITIONS

1) Regarding "Ray 1.49": We sent our upgraded version of this ray-tracing code to Art Newhall at WHOI and Paul Baxley at SPAWARSSC for updating the OALIB website.

2) Regarding "CAFI": We sent our version of Stan Flatté's statistical acoustic code to Mike Porter at HLS Research for inclusion in the OALIB website.

PUBLICATIONS

Andrew, Rex K., James A. Mercer, Bradley M. Bell, Andrew A. Ganse, Linda Buck, Timothy Wen, and Timothy M. McGinnis, PhilSea10 APL-UW Cruise Report: 5-29 May 2010, APL-UW TR 1001, October 2010. [Not refereed.]

Andrew, RK, BM Howe, and JA Mercer, (2011). Long-time trends in ship traffic noise for four sites off the North American West Coast, *J. Acoust. Soc. Am*, **129**(2), pp 642-651, [Refereed]

Udovydchenkov, Ilya A., Michael G. Brown, Timothy F. Duda, James A. Mercer, Rex K. Andrew, Bruce M. Howe, Peter F. Worcester, and Matt A. Dzieciuch, A modal analysis of the range evolution of broadband wavefields in a deep-ocean acoustic propagation experiment I: low mode numbers, *J. Acoust. Soc. Am.*, submitted. [Refereed.]
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APL - North Pacific Acoustic Laboratory

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. ***The North Pacific Ambient Noise Laboratory***, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consists of the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Hydrophone arrays

designated as D, E, F, and R have been declassified. Arrays we designate as G, H, I, J, K, L, M, N, O, P, and T remain classified.

The second avenue includes highly focused, comparatively short-term experiments. We have completed a pilot study/engineering test and an experiment in the ***Philippine Sea*** called **PhilSea9** and **PhilSea10**, respectively [1]. See Figure 1. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the Distributed Vertical Line Array (DVLA) from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT). Analysis of environmental data from PhilSea10 is underway, and we have now received the acoustic data from the DVLA.

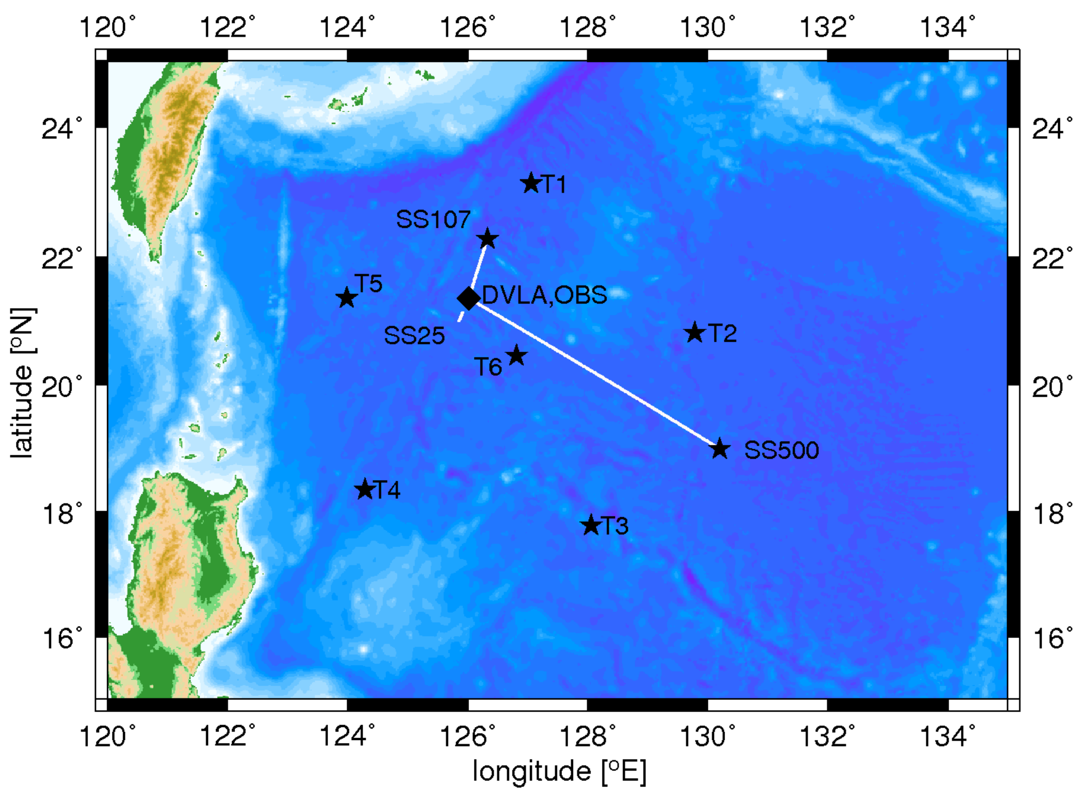


Figure 1. Principal activity locations for PhilSea9 and PhilSea10

WORK COMPLETED

Although our current effort is focused on the avenues described above, a large number of publications are also still coming from previous experimental work, e.g., LOAPEX [2] (See the Publications section.).

North Pacific Ambient Noise Laboratory-

The NPAL North Pacific Ambient Noise Laboratory was installed in the early 1990s as part of the Acoustic Thermometry of Ocean Climate program and utilizes undersea hydrophone arrays owned by the US Navy. In addition, shore-based equipment is located at Navy and non-Navy shore facilities. Complicating the transfer of data media and hardware components from the shore sites to APL-UW are the required auditable trails of information on storage media and hardware. The current procedures, protocols, and documentation requirements devised and negotiated by APL-UW and Navy personnel for these transfers are described in Ref [3].

Like most older electronic hardware, maintenance is a continuing issue. Hindering our monitoring and maintenance efforts for arrays J, K, L, M, N, O, P and T has been a loss of our secure communication link to the shore facility. The problem began with the requirement for a new type of secure transfer hardware. After much frustration with the new hardware it was finally determined that the hardware was defective. Now that the hardware has been replaced it appears to be incompatible with the University of Washington's modem exchange system. Recent successes from an off-site location using XFINITY via Comcast have been successful. This commercial system may be the solution going forward.

Other significant problems for these sites include 1) hung computers (obviously this can be addressed more effectively once a remote communication link is established; 2) system hard drives that become full without the monitoring capability (Site visits to service these receivers have recovered nearly 200GB of data. These data have been transferred manually to the APL Data Center for archiving.); 3) Empty data files due to IRIG timing channel dropouts (A software upgrade has solved the loss of data but the cause of the IRIG channel glitch is still unknown.); and 4) Motherboard failures (The problem is related to cooling fan failures. Unfortunately, these motherboards are no longer manufactured. Replacement boards are being identified.).

The shore station for receiver site R has been located at Naval Air Station, Barbers Point, HI. Due to several failures of the air conditioning (A/C) system, a remotely monitored temperature indicator was installed. A subsequent failure of the A/C system was detected and system down time was significantly reduced.

Following the Base Realignment and Closure action for NAS Barbers Point, the Site R building remained available as a shore site for several years until recently. All APL-UW equipment for site R was re-calibrated, removed and placed in storage in Hawaii. A portion of the cable route for site R will remain on Navy controlled property. Application to a land-board has been submitted to re-locate the receiver equipment over the cable route on this Navy controlled property. Since it is apparently more difficult to get approval for a temporary facility, a new facility of some type will be required.

Receiver arrays E and F terminate at a building on San Nicholas Island, CA. This facility has been closed and is no longer available. The APL-UW equipment will have to be removed. We are waiting for Navy approved transportation to San Nicholas Island to accomplish this task. Routine remote checks from Seattle of the transmitter site on Kauai indicate that the system is still fully functional.

The distribution of one-hour ambient noise level data over a single year at all of our North Pacific receiver sites became of interest to the NOAA Sound Mapping group. In this case, the level measure is the arithmetic average over one hour. Statistics for arrays D, F, G and H have previously been published in the open literature, but extracting the statistics for these one-hour averages was a simple matter of adjusting some post-processing code and applying it to the calibrated archival datasets for those sites.

The procedure was not as simple for arrays J, K, L, M, N, O, P, and T. Fully calibrated archival data have never been produced for these sites --- the missing correction factor involves the transfer function of an interface card in the APL instrumentation rack, which introduced 1 to 3 dB of frequency dependent loss. Correction files were built for all these sites. Once this was done, the archival data (collected up to approximately 2007) was further processed to produce data calibrated with all known correction functions, and then compiled into one-hour level statistics for a given year. The results for sites D, F, G, H, J, K, L, M, N, O, P, and T were written to portable binary netCDF files and sent to HLS Research, La Jolla, California. Results for site K are shown in Figure 2.

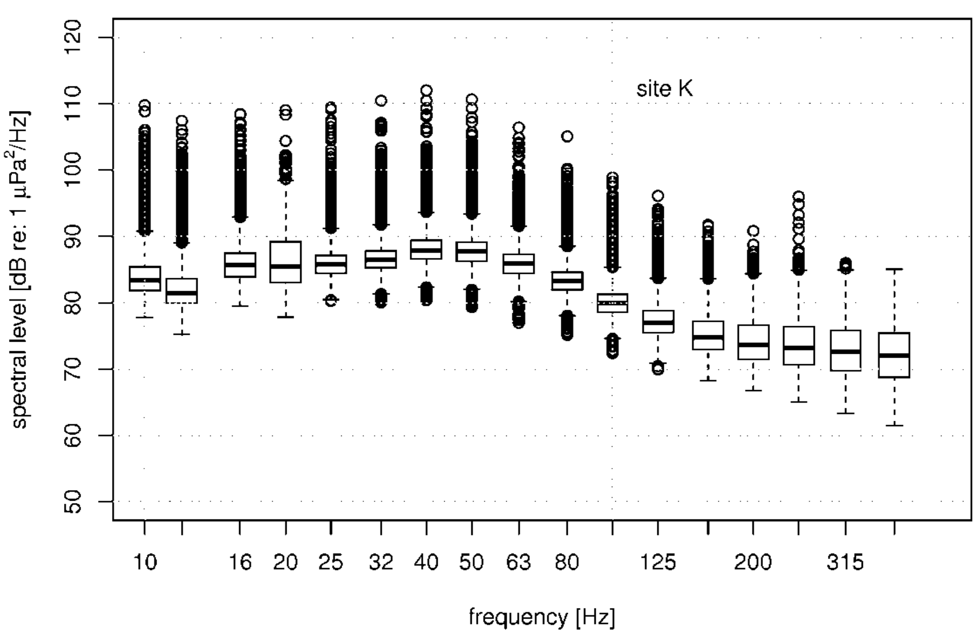


Figure 2. One-hour average ambient noise level for site K.

NEW RESULTS

Philippine Sea-

The detection and removal of outliers from the **Philsea09** acoustic dataset has allowed progress in analysis. Sources of contamination of the data included noise due to passing ships, glitches in the power amplifier that supplied the signal to the projector, and unidentifiable man-made signals in the water. The affected data were marked and removed. The result of this cleanup effort may be seen by comparing the bottom panel of Figure 4 of this report with the top panel of Figure 3 from the FY2011 annual report.

Time-independent and time-dependent Monte Carlo PE modeling efforts were described in the FY2011 annual report. These simulations required generation of random instances of displacement fields described by the GM81 model spectrum. Following Colosi and Brown [4] these displacements were converted to perturbed sound-speed fields using an approximation originally suggested by Stan Flatte [5]. The approximation is that the N^2 profile may be used in lieu of the potential sound speed gradient for perturbation of the background sound speed profile by the internal wave displacements. This approximation seems to have been applied, for example, by Xu [6] in MCPE (Monte Carlo Parabolic Equation) modeling. The validity and effect of the approximation in the Philippine Sea were not known, and therefore we conducted a comparison between this approximation and the more accurate model, which instead uses the potential sound speed gradient to calculate the perturbed sound-speed field.

The comparison involved writing a C-language code to compute the perturbed sound-speed field with the second, more accurate method and performing a time-independent MCPE experiment that employed this new code. Approximately 225 random perturbed sound-speed fields were used in the model experiment. The MCPE predictions for the scintillation index (SI) using the N^2 approximation vs. the potential sound speed gradient are shown in Figure 3, along with estimates of the SI made from the **Philsea09** acoustic data. This work was presented at the ASA Hong Kong conference.

The MCPE modeling efforts described above (and more completely in the FY2011 report) might be thought of as a possible pre-experiment scenario. As mentioned previously, these models included as a background environment low-passed, averaged sound-speed and N^2 profiles that were made using CTD casts taken during the 2009 cruises. We could have used, alternatively, profiles of the same quantities from the Levitus database. Aside from this detail, before conducting the **Philsea09** and **Philsea10** experiments, we had no more information about sources of fluctuation of the sound-speed field in the region, and in particular, about appropriate values for the parameters of the GM spectrum. Aside from the CTD profiles collected during the experiment, the ocean models used in these modeling efforts were not adjusted according to, for example, the environmental measurements made by the CTD sensors on the DVLA. An interesting question might be, “How well can we do at predicting acoustic intensity fluctuation measures using MCPE with a GM spectrum, without spending the time and money to measure the local fluctuations in sound speed?”

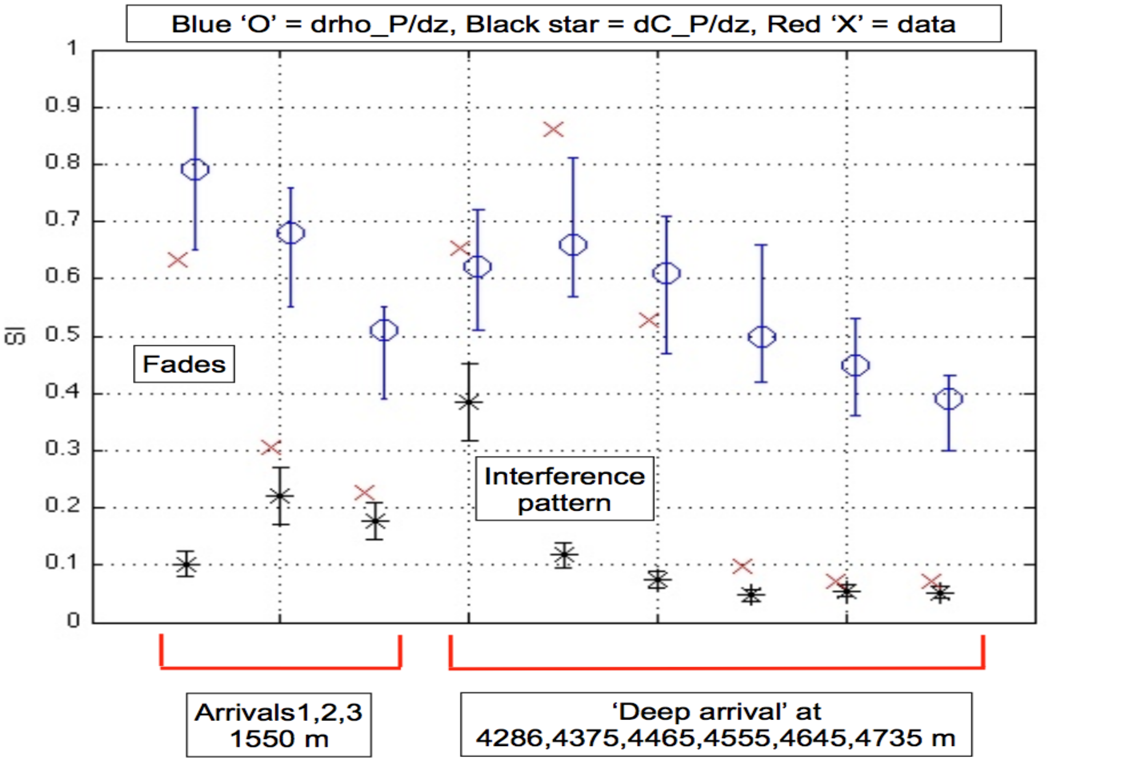


Figure 3. Shown here are the MCPE model predictions of SI using the N^2 approximation (blue circle) vs. using the potential sound speed derivative (black star) in calculating the perturbed sound speed field from the displacement. The SI estimates made from philsea09 measurements (red x) are shown for comparison. The boxes labeled "Fades" and "Interference pattern" are discussed in the section describing the mixed-layer hypothesis.

The above question is posed making at least one significant assumption: that the GM spectrum is an accurate representation of sound-speed fluctuations in the Philippine Sea. It is apparent from the APL/UW **Philsea10** 500 km CTD transect that there is a strong large-scale range-dependence to the sound speed profile. In addition, peaks at tidal frequencies are observed in the spectrum of sound speed variability measured by the CTD sensors on the DVLA. These two pieces of evidence suggest that a range-independent background sound-speed field perturbed by GM spectrum internal waves would not be a complete model of the Philippine Sea propagation environment. Construction of a model or models that address these concerns has been proposed for future work. This proposed work would go beyond the standard MCPE approach, however, which has generally made the same assumptions outlined above [6,7]. We are planning to adjust the "strength parameter" in the MCPE model as a part of our future work; this result may be later compared with more involved models that we have proposed to investigate. The adjusted-strength models may also be compared to our previous modeling as a simple first-cut attempt at answering the question posed in the previous paragraph.

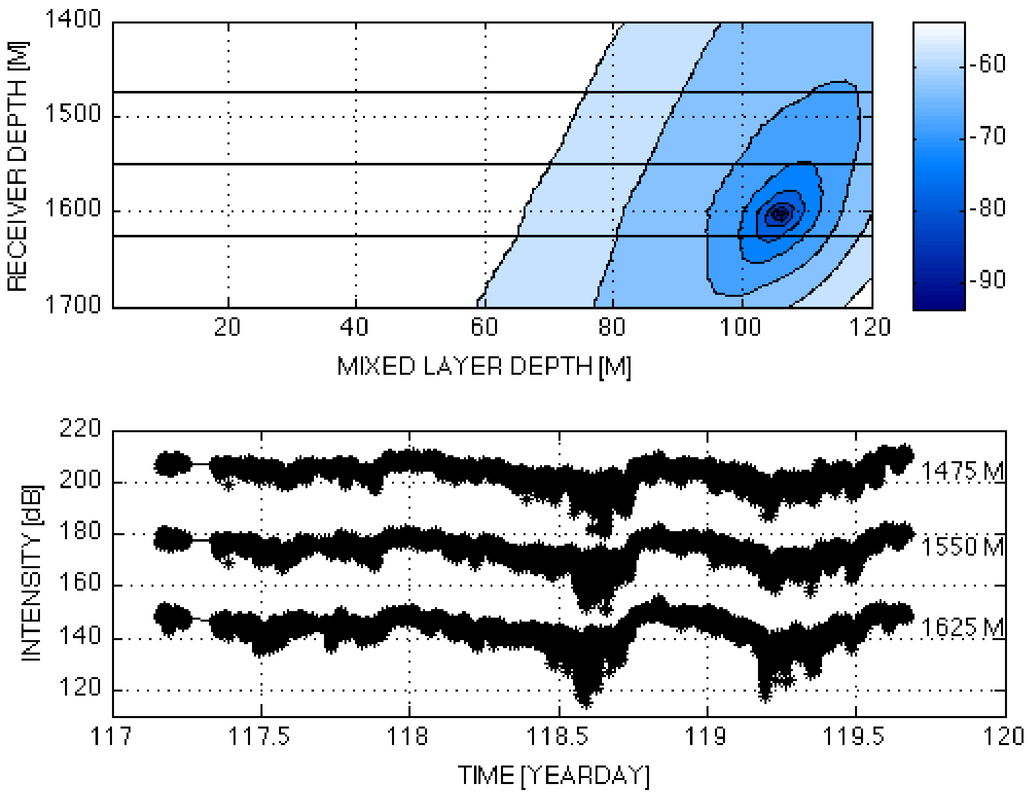


Figure 4. The upper panel shows the predicted acoustic intensity for the shallow-turning path for receiver depths from 1400 to 1700 m vs mixed layer depth. Five dB contours of intensity are plotted. The horizontal black lines represent the depths of the hydrophones referred to in the lower panel. The lower panel shows the observed acoustic intensity for hydrophones at 1475, 1550, and 1625 m depth, as indicated by labels to the right of each record. An offset has been added to each timeseries for visualization.

We have now also analyzed the CTD data collected on the DVLA in order to make an estimate of the GM strength parameter. Significant (up to 90 m) blow-downs of the DVLA occurred during the month of its deployment. These blow-downs introduced fluctuations into the temperature and salinity records relating to the change of depth of the sensors. The measurements were interpolated in depth in order to attempt to remove this instrument-caused fluctuation. Several interpolation methods were examined. The estimate of GM strength was much more strongly influenced by the choice of filter used to eliminate frequencies outside the internal wave spectral bounds than by the choice of interpolation method. An estimate of the GM strength appropriate for the Philippine Sea was made and the MCPE model adjusted accordingly. These simulations are currently running, and the results will be presented at a later date.

During the 2009 pilot study **PhilSea09**, deep (roughly ten dB) fades in acoustic intensity lasting for several hours were observed on hydrophones at several depths spanned by the shallow array. These fades were observed in acoustic arrivals having shallow upper turning points (~60 m), and

not in arrivals with deeper upper turning points (~200 m). The observed fades were not predicted by time-dependent Monte Carlo Parabolic Equation (MCPE) modeling with random GM internal wave displacements of a range-independent background.

Some of the mismatch between Monte Carlo PE and the observed intensity fluctuations is thought to be due to interaction with the mixed layer in **PhilSea09**. To explore this possibility, the same range-independent profile used in the MCPE modeling was modified to include a mixed layer. Results from acoustic mode propagation through the modified sound speed profile support this hypothesis; see Figures 4 and 5 of this report.

The 60-hour timeseries of acoustic intensity resulting from APL-UW transmissions in **PhilSea09** are shown in the bottom panel of Figure 4. Deep fades of similar magnitude are visible in the records at each of the three hydrophones, with an apparently high coherence. The top panel in Figure 4 shows the modeled effect of a mixed layer on the acoustic intensity for receiver depths including those of the hydrophones that recorded the deep fades. The mode-propagation modeling predicts fades of similar magnitude given the observed mixed layer depths, and also predicts a high coherence between the three receivers.

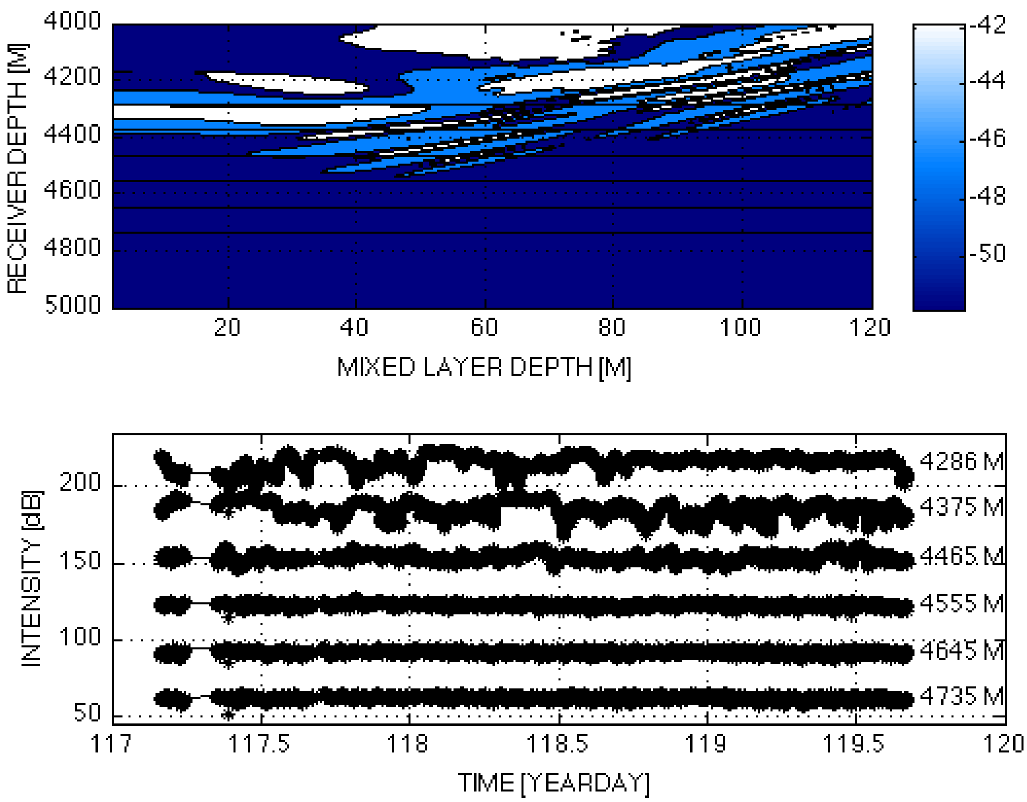


Figure 5. The upper panel shows predicted acoustic intensity for a shallow-turning path forming the deep arrival for receiver depths between 4000 to 5000 m vs mixed layer depth. Five dB contours are plotted. The lower panel shows the observed acoustic intensity for six hydrophones on the deep array. An offset has been added to each timeseries for visualization.

The bottom panel of Figure 5 shows the intensity timeseries from the same transmissions, recorded on the deep subsection of hydrophones on the DVLA. The intensity recorded at 4286, 4375, and 4465 m depth exhibits much larger fluctuations than the intensity recorded at depths of 4555, 4645, and 4735 m, and the intensity at the shallower three depths does not appear to be coherent.

The top panel of Figure 4 shows the modeled effect of a mixed layer. When the mixed layer is absent, or very shallow, the intensity varies for the top three receivers by up to ten dB. As the mixed layer deepens, a complicated interference pattern is formed with up to ten dB differences from what would be expected with no mixed layer—but the interference causes differences smaller than five dB for the three deepest receivers shown in Figure 4. These features are broadly consistent with the observed intensity variations.

Independent predictions of log-amplitude variance were made using Munk-Zachariasen theory to compare to measurements on acoustical signals transmitted during the **PhilSea09** pilot study/engineering test. This comparison involves 284 Hz center frequency signals transmitted over a 107 km path. Statistics were compared for three paths, one with a single upper turning point at about 60 km, and two with two upper turning points about 200 km. The theoretical calculation required an estimate of the Fresnel tube structure around the "unperturbed" eigenray. The estimate was made using Bellhop: an example is shown in Figure 6. Predictions for the two paths with deeper upper turning points compare well: predictions for the other path, which has a shallow upper turning point, do not. Estimates of the scintillation index based on log-amplitude are shown in Figure 7. Compare with Figure 3 arrivals 1,2, and 3, respectively.

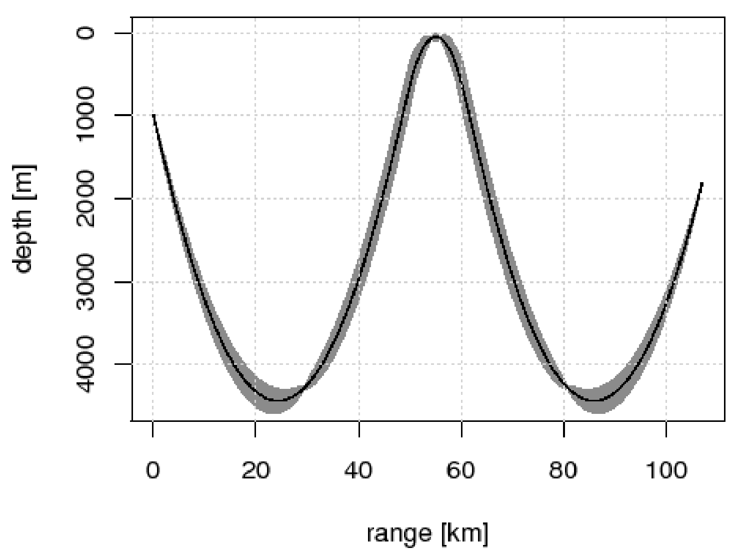


Figure 6. Fresnel tube around one of the Philippine Sea 2009 experiment eigenrays, frequency 284 Hz.

These results were presented at the May 2012 Hong Kong Acoustical Society of America meeting for the Asian Marginal Seas special session [8]. A manuscript describing these results has been prepared for the JASA special issue on the Philippine Sea experiment.

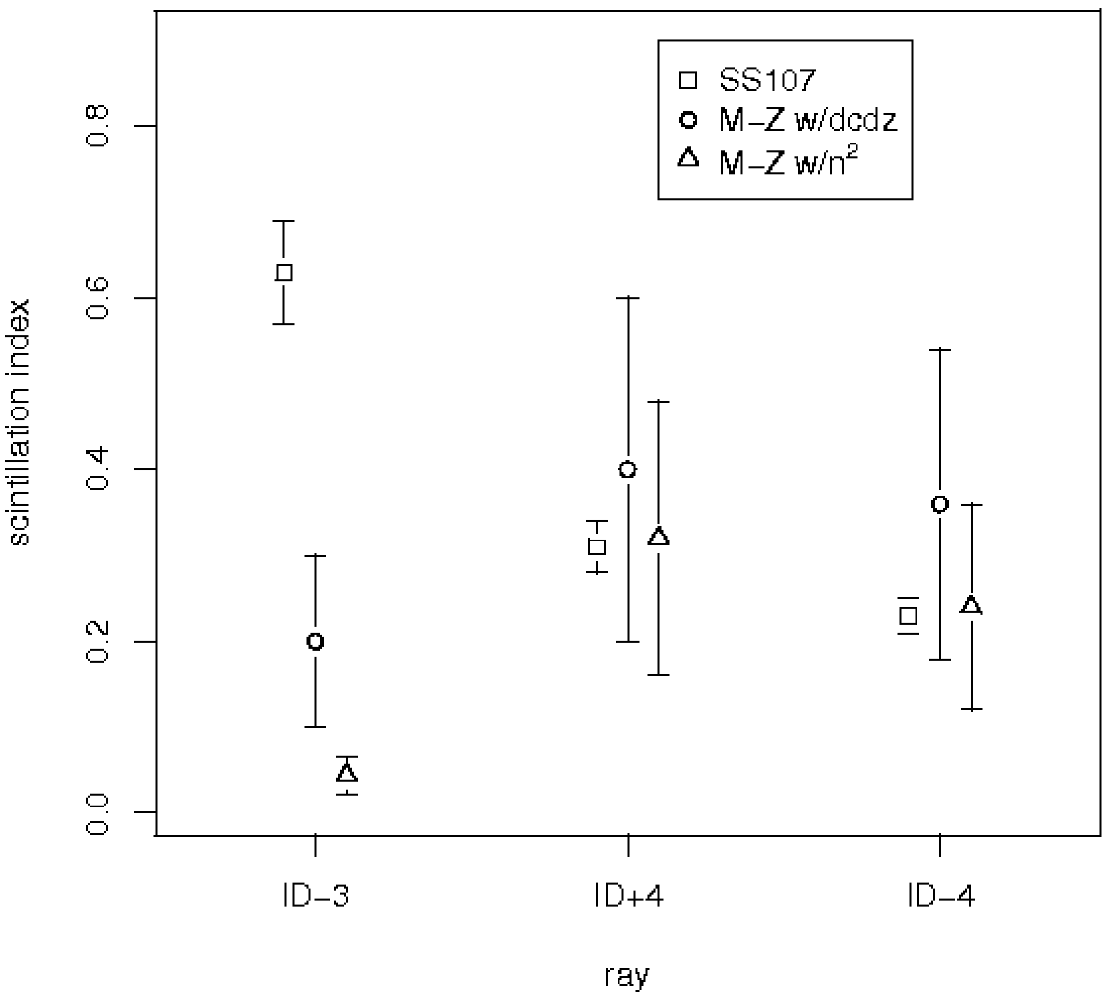
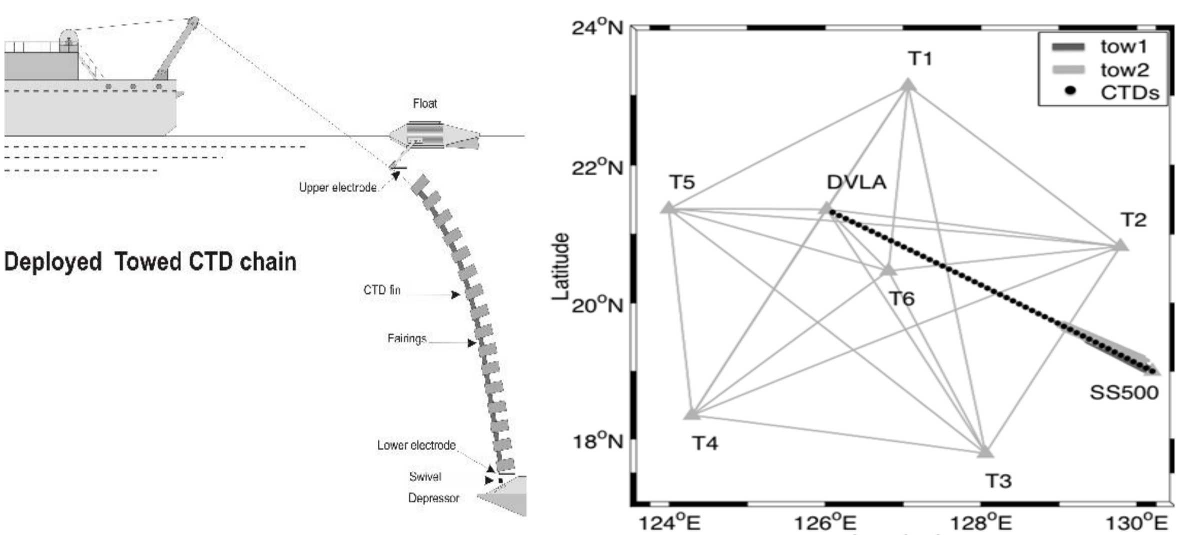


Figure 7. Measurements and predictions of scintillation index versus path, Philippine Sea 2009 experiment. Two different scales in the theoretical expression were used, one involving the sound speed gradient ("dcdz") and the other using the Brunt-Vaisala frequency ("n^2"). Munk-Zachariasen theory appears to make consistent predictions for paths ("rays") ID+4 and ID-4 at this range and this frequency, but not for path ID-3.

New results for horizontal statistics of ocean spice and internal waves have been obtained from the Towed CTD Chain (TCTD). Spatial statistics of internal waves and ocean “spice” (neutrally-buoyant thermohaline variations) are important for modeling the effects of oceanic variability on ocean acoustic propagation, to understand and predict phenomena such as acoustic intensity variations and deep fades at receivers. Vertical statistics have traditionally been the focus of pertinent experiments, but little or nothing has yet been learned about the aspect ratio and joint vertical and horizontal statistics in actual measurements, largely due to the difficulty in taking the data required for such analyses. To this end, APL-UW deployed an 800m version of a towed CTD chain (TCTD) [9] in the **PhilSea10** experiment, attempting to densely sample temperatures and conductivities in a 2D ocean slice along towpaths of order 100km. (See Figure 8 for a notional diagram of the system and the experiment geometry with respect to the rest of that experiment.) While the instrument performed poorly and produced only a small subset of the data expected in the tows, analysis was still possible by taking advantage of a sequence of CTD casts taken nearby in space and time to the analyzed TCTD tow. From analysis of this comparatively small amount of tow data we have obtained horizontal spectra of internal waves and spice, as well as cross-spectra which describe the correlations between multiple sensors in concurrent horizontal towpaths. The latter in particular is new in the literature as far as we are aware – although the original equipment was meant to result in full 2D (horizontal/vertical) spectra, and the heavily troubled tow data prevented calculating this quantity, we can still calculate the cross-spectra between a set of towpaths at different depths. These help constrain the full 2D spectrum as the community develops future models of spice distribution based on field measurements.



(a) (b)

Figure 8. (a) Diagram of the 800m towed CTD chain apparatus as deployed behind the ship. (b) The 2010 experiment geometry – a 500km linear sequence of CTDs were taken between the DVLA and ship stop SS500; the two TCTD towpaths overlapped each other and the easternmost 100km of the CTD casts.

The TCTD pressure, temperature, and salinity measurements are used to compute the density-based and soundspeed-based components of vertical displacement, each via the same equation of state [10], according to the methods of Henyey et al [11]. Other APL-UW work has already focused on studying the vertical variation of spice in the Philippine Sea by similar methods [11,12]. Outside of APL-UW, analysis by Colosi et al [13] takes a different approach to studying that vertical variation. Our horizontal analysis also builds off earlier related works including that by Ferrari and Rudnick [14] and Klymak and Moum [15]. Those works used undulating towfishes to take CTD measurements at one depth at a time, allowing us to analyze horizontal spectra of internal waves [14,15] and spice [14] in isolation at the one depth. By using a towed chain, we simultaneously measure multiple depths of the same quantities, allowing us to calculate new cross-spectral information. As in Klymak and Moum [15] we present our spectral results in terms of spectra of horizontal gradients in vertical displacement, i.e. "displacement slope".

The analysis relies on linearization of the density and soundspeed measurements around smooth background fields. The great vertical decimation in the TCTD measurements due to equipment malfunctions prevented estimation of these background fields, but by shear serendipity a sequence of CTD casts every 10 km had just been completed along the same path as the tow, and these were used to provide the background field for the analysis. Figure 9 shows the spatial and temporal coverage of the CTD and TCTD data used for the analysis. Tow 1 was not used for the analysis – it had far less coverage of acceptable-quality data, and also did not have the two additional Microcat CTDs attached to the sea cable to assist with the system's troubled pressure measurements (as tow 2 had).

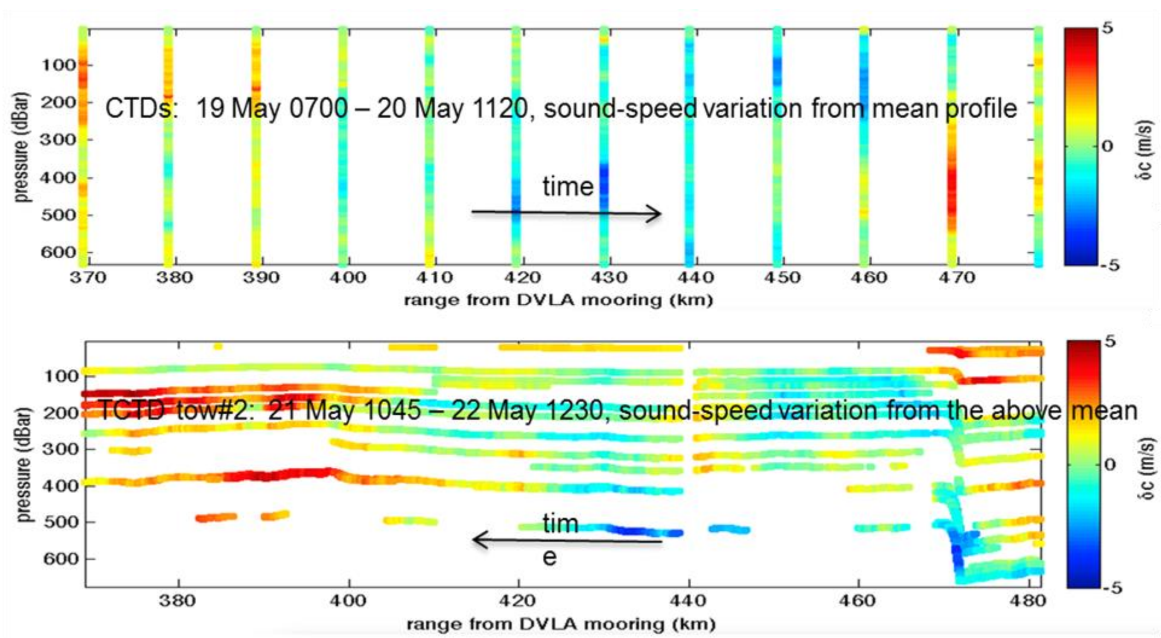


Figure 9. The data coverage of the CTD data (top) and collocated tow 2 TCTD data (bottom), expressed in plots showing soundspeed variations about the mean of the CTD casts over the TCTD ranges. The CTD casts were taken while sailing away from the DVLA, then at SS500 the ship turned around and started towing the TCTD toward the DVLA.

The data needed to be extensively cleaned and conditioned. This included: removing outliers and systematically troubled temperature and conductivity data, recalibrating conductivity data by again taking advantage of collocated CTD casts along the tow, fitting a cable model to the particularly poor pressure sensor data with the aid of the Microcat CTDs on the cable, and interpolating the data to horizontal paths to remove fluctuations due to the pressure changes. However, validation of the spectral results against theoretically predicted patterns, as well as comparisons of aspects of the results with similar results in previously published work, give confidence in the soundness of these results calculated from the **PhilSea10** TCTD.

Figure 10 shows log-log horizontal wavenumber spectra of (Figure 10a) the displacement slopes representing internal wave distribution and in Figure 10b the difference between the soundspeed-based and density-based displacement slopes, representing spice distribution. In Figure 10a the red line is the soundspeed-based displacement slope spectrum, the black line is the density-based displacement slope spectrum, and the green line is the real part of the cross-spectrum between the density- and soundspeed-based displacement slopes. That real part of the spectrum is close to that of the density-based one, and the imaginary part of that same cross-spectrum is not on this plot as it is close to zero, both of which are as theoretically expected. These are theoretically expected given no correlation between the internal waves (which propagate according to wave theory) and spice (which advects); in that case the cross-spectrum should equal the real-valued density-based one, so that there is no real part. Additionally, since the density-based spectrum is due to the internal waves while the soundspeed-based spectrum is due to both internal waves and spice, the soundspeed-based spectrum is higher than the density-based one, as seen in the figure. These density- and soundspeed-based spectra are both variations of the displacement slope spectrum predicted by Garrett Munk (GM) theory [16] – the power level is that of the towed spectrum, while the cut-off wavenumber is the 1e-1 cpm from GM theory multiplied by the ratio of inertial to buoyancy frequencies (f/N), and the roll-off continues as k^{-1} from there. At wavenumbers above about 1e-2 cpm, the spectra rise again due to turbulence, as analyzed for example again in Klymak and Moum's papers [15,17]. In Figure 10b the spectra depict spice variability by quantifying the variations in difference between soundspeed-based displacement slope and density-based displacement slope. As in Ferrari and Rudnick's [14] experiment the spice spectra are relatively flat and constant in depth at the depths shown here. The rise in power at high wavenumbers due to turbulence is still seen in the same wavenumber range as in Figure 10a.

Ironically, overall the amount of spice measured on the TCTD chain in the Philippine Sea 2010 experiment was fairly low when analyzed spectrally, which was initially of concern because it conflicted dramatically with the vertical analysis from the CTDs [11]. The spatial representation of the spice in Figure 11 explains the disparity and the irony. As is done in the horizontal analysis, the profiles of spice in Figure 11 are the difference between the soundspeed-based and density-based displacement (the spectra are later calculated from the vertical gradients of these profiles in the vertical analysis). These profiles show a poorly understood minimum in the spice distribution right at the depth range of the TCTD measurements! With a better understanding and ability to model the spice, future experiments may be able to better predict such patterns in the spice in order to measure it more efficiently and consistently.

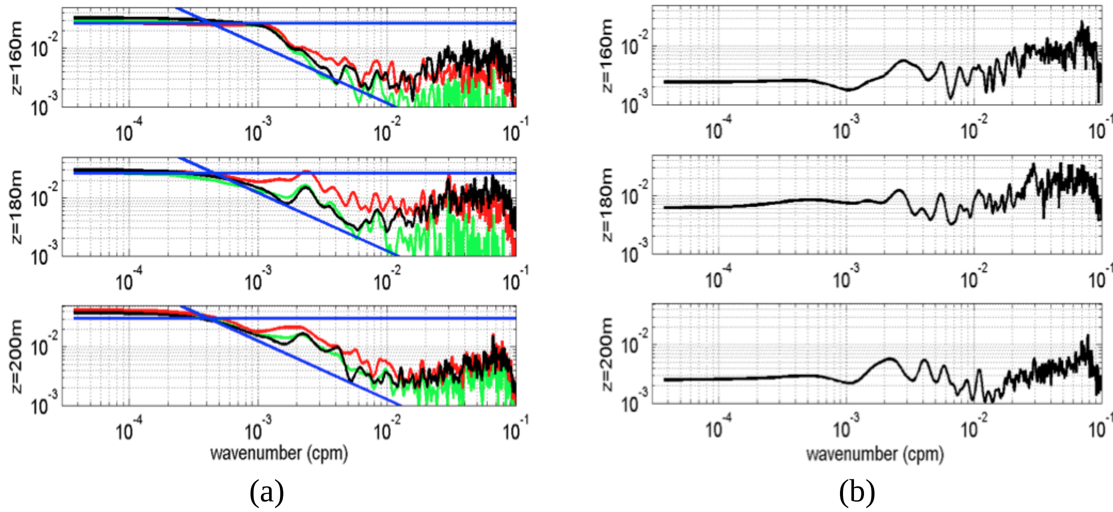


Figure 10. Log-log horizontal wavenumber spectra of (a) the displacement slope representing internal wave distribution and (b) the difference between the soundspeed-based and density-based displacement slopes, representing spice distribution. Features in these plots are discussed in the text.

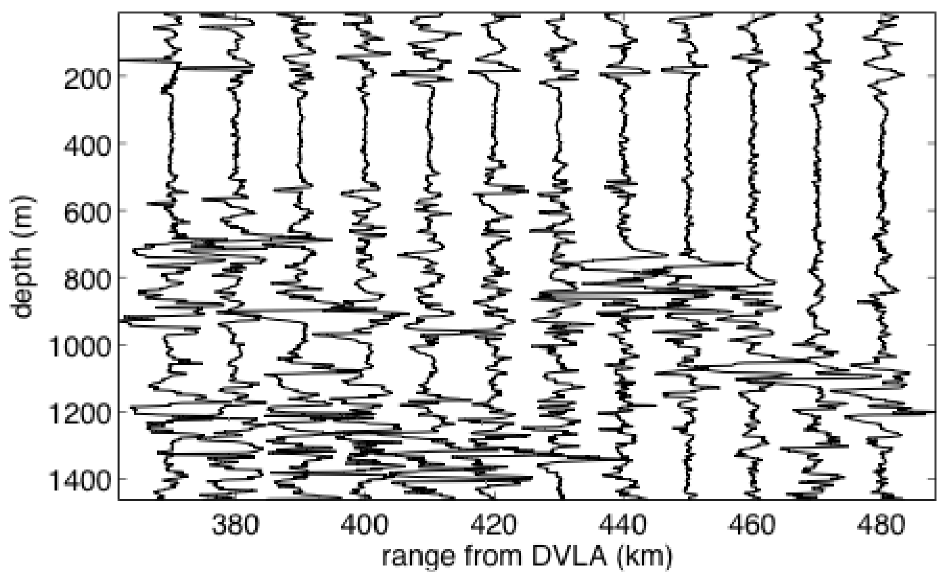
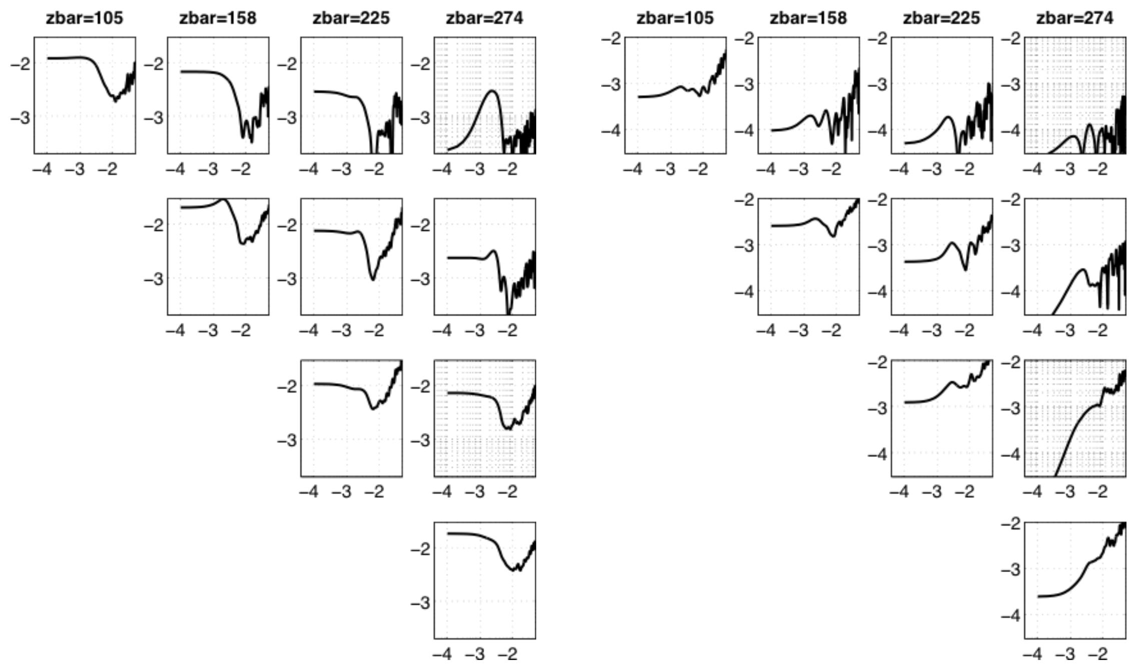


Figure 11. Spice distribution along the TCTD towpath as calculated from the 12 CTD casts used for the background field. These profiles here are the difference between the soundspeed-based and density-based displacement. Note the ironic (and not well understood) minimum in spice distribution right at the depth span of the TCTD instrument – this can be considered another aspect of the motivation to better understand and model spice, such that new experiments to measure it can do so more efficiently and consistently!



(a) (b)

Figure 12. Arrays of horizontal wavenumber auto- and cross-spectra at four sensor depths, in the mean over the ranges of the tow. The spectra describe the variability in (a) density-based displacement slope representing internal wave distribution, and (b) the difference between the soundspeed-based and density-based displacement slopes representing spice distribution. The arrays in (a) and (b) each depict horizontal cross-spectral combinations at four sensor depths in the towed CTD chain, whose mean depths are list as "zbar" along the tops of the array columns (the arrays of spectra are symmetric so only the upper triangular half of the arrays are shown). The axis labels are minimal to accommodate the many plots: note axes are log-log, x-axes are horizontal wavenumber in cpm, y-axes are power spectral density in meters, and both axes display the log10 of their respective quantity. Features in these plots are discussed in the text.

The ultimate contribution of the work is a set of auto- and cross-spectra of spice distribution in the horizontal, at a number of simultaneous depths, which may help to constrain the 2D (in x and z) distribution of spice in the ocean. (Or perhaps just in the Philippine Sea at that time of year – it is not yet known if the distribution of spice will be seen as consistently geographically and temporally as the internal wave background seems to be.) Figure 12 shows arrays of horizontal wavenumber auto- and cross-spectra at four sensor depths, in the mean over the ranges of the tow. These spectra describe the variability in Figure 10a the density-based displacement slope representing internal wave distribution, and in Fiugure 10b the difference between the soundspeed-based and density-based displacement slopes representing the spice distribution. The mean depths of each sensor (corresponding to the columns and rows of the array) are list as "zbar" along the tops of the array columns; the arrays of spectra are symmetric so only the upper triangular half of the arrays are shown. In Figure 12a we note internal wave power rolling off at wavenumber similar to that expected by GM theory as in Figure 10a, the power rising again at wavenumbers greater than 1e-2 cpm due to turbulence, and the additional roll-off in the cross-

spectra with increasing depth separation of the sensors. Similarly in (12b) we see the rise in power above 1e-2 cpm due to turbulence, roll-off in the spice cross-spectra with increasing sensor depth separation which is greater than that seen for the internal waves in (10a). Lastly in comparison with Figure 10b we can see a hint in the spectra of at that drop in spice level below about 250m.

The vertical and the horizontal analyses of the CTD and TCTD data are being written up in separate journal papers which are expected to be submitted to JASA in time for the special issue on Deep Water Ocean Acoustics [18].

New results from the LOAPEX data have been obtained using the full resolution of the data. It was found that the first four (southeastern) CTD stations included spice fronts. Figure 13 shows the front at the station 50 km from the receiver array. These fronts invalidate the processing algorithm, because the "background" sound speed profile is assumed to be the low-pass of the sound speed. The sharp fronts are, however, obviously part of the background. These fronts likely have an important effect on acoustic propagation, but without knowing the slope of the front, it is not possible to calculate the effect. Completion of the full resolution reanalysis of the PhilSea data is imminent. We are planning to complete a paper on this subject for the special issue of JASA.

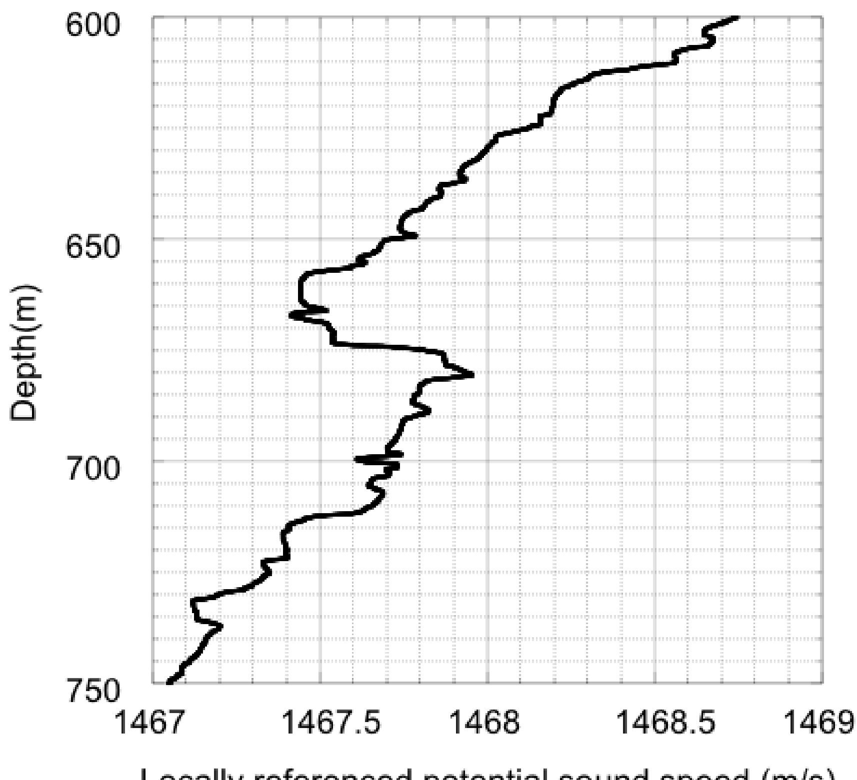


Figure 13. A spice front at station T50. With such a front, the "background" profile cannot be assumed to contain only low wavenumber content. (The horizontal axis is the sound speed minus the integral from the surface of its adiabatic derivative.) Similar fronts exist at the first four stations, but not beyond.

Similarly, deducing the vertical properties of the spice from the CTD profiles is insufficient for including them in acoustic propagation without simultaneously understanding their horizontal structure. A beginning on understanding the simultaneous vertical and horizontal structure of spice is an important focus of the work stemming from the data collected with the Towed CTD Chain.

RELATED PROJECTS AND COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), I. Udovydchenkow (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D'Spain who is funded by the signal processing code of ONR.

Steven R. Ramp, President and CEO, Soliton Ocean Services, Inc., requested APL's PhilSea10 CTD raw data files. These files have been sent and receipt has been acknowledged.

APL-UW provided technical advice to the NOAA Soundscape Mapping Working Group, and at the request of the working group, ambient noise data were sent to the HLS Research, La Jolla, California.

2006 RSMAS Acoustical Communication Experiment: We located and collected multiple datasets acquired during a 2006 RSMAS experiment requested by Prof. Brown/ RSMAS/UMiami that used the Kauai ATOC/NPAL source at the end of permitted operations. This experiment transmitted a special signal of Prof. Brown's design. The transmission was captured by multiple APL network receivers. The data collected by the Barber's Point system was deemed to be the best dataset. Due to classification concerns, the raw Barber's Point files were not given to Prof. Brown: instead, single channel acoustical records were stripped out from the raw files. Also located were acoustical records collected by the APL acoustic Seaglider which was deployed in the region for LOAPEX and this experiment. The transmission files from the Kauai computer were recovered and returned to APL. The entire dataset of all pertinent releasable files (Kauai, Barber's Point, and Seaglider) was about 20GB. Everything we could determine about the experiment was documented in an associated memo, and everything shipped to Prof. Brown.

APL-UW supported H.C. Song/MPL with analysis of data collected by the Barber's Point system in order to determine if any of the standard collections captured the acoustic communication signals transmitted during the 2010 LRAC experiment. Transmission loss calculations and power spectral density measurements suggest that the signal at the receiver was too weak to provide useful data.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

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Udovydchenkov, Ilya A., Michael G. Brown, Timothy F. Duda, James A. Mercer, Rex K. Andrew, Peter F. Worcester, Matthew A. Dzieciuch, Bruce M. Howe, and John A. Cososi, "Modal analysis of the range evolution of broadband wavefields in the North Pacific Ocean: low mode numbers," *J. Acoust. Soc. Am.*, **131**(6), June 2012.

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Udovydchenkov, Ilya A., Ralph A. Stephen, Timothy F. Duda, S. Thompson Bolmer, Peter F. Worcester, Matthew A. Dzieziuch, James A. Mercer, Rex K. Andrew, and Bruce M, Howe, "Bottom reflections from rough topography in the Long-range Ocean Acoustic Propagation Experiment," *J. Acoust. Soc. Am.,* submitted.

Chandrayadula, Tarun K., Kathleen E. Wage, Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, and Bruce M. Howe, "Reduced rank models for travel time estimation of low mode signals," *J. Acoust. Soc. Am.,* submitted.
Udovydchenkov, Ilya A., Michael G. Brown, Timothy F. Duda, Peter Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, Bruce M. Howe, and John A. Colosi, "Weekly dispersive modal pulse propagation in the North Pacific Ocean," *J. Acoust. Soc. Am.*, NPAL special issue.

Chandrayadula, Tarun K., Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, and Bruce M. Howe, "Observations and transport theory analysis of low frequency, long range acoustic mode propagation in the Eastern North Pacific Ocean," *J. Acoust. Soc. Am.,* NPAL special issue.

Ganse, A. A., F.S. Henyey, and J.A. Mercer " Horizontal statistics of ocean spice and internal waves measured with a towed instrument chain in the Philippine Sea 2010 experiment," *J. Acoust. Soc. Am.,* NPAL special issue.

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APL - North Pacific Acoustic Laboratory

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. ***The North Pacific Ambient Noise Laboratory***, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consists of legacy SOSUS hydrophone receivers in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory.

The second avenue includes highly focused, comparatively short-term experiments.
We have completed a pilot study/engineering test and an experiment in the ***Philippine Sea*** called **PhilSea9** and **PhilSea10**, respectively [1]. See Figure 1. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the Distributed Vertical Line Array (DVLA) from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT).

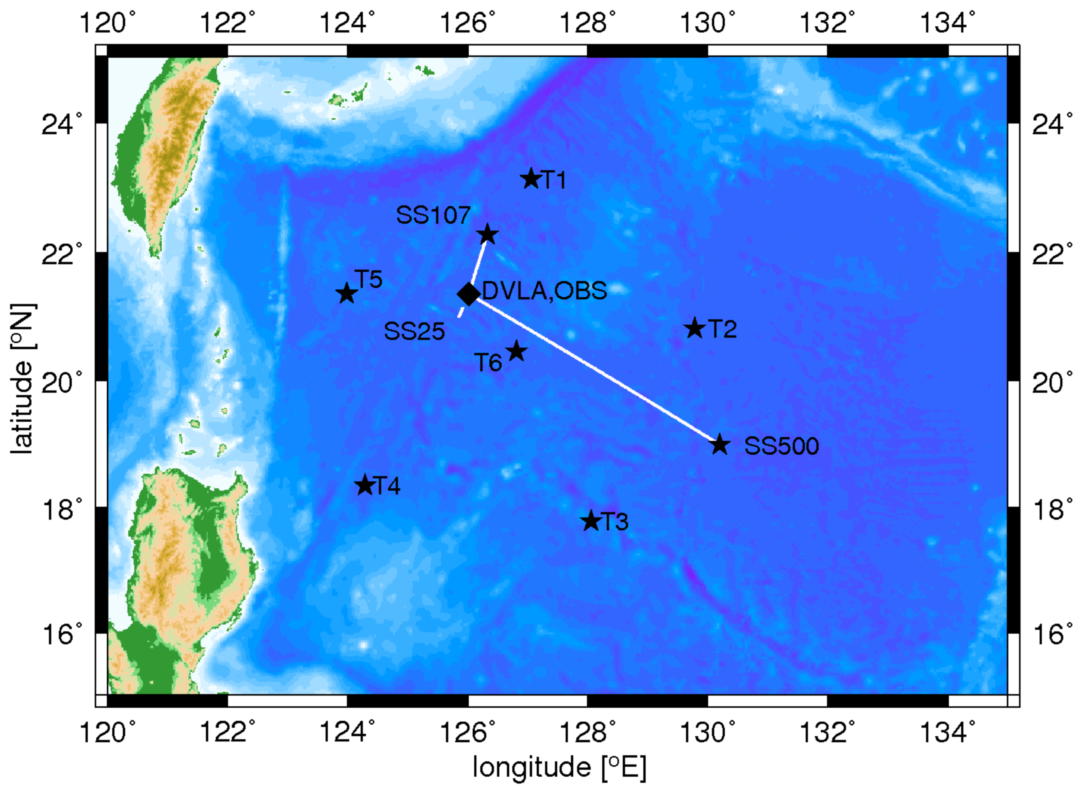

Figure 1. Principal activity locations for PhilSea9 and PhilSea10

WORK COMPLETED

Preliminary processing on the **PhilSea10** data was completed in order to verify that we had good data in preparation for more refined processing. This involved modifying the existing processing code for the actual transmissions from both the HX554 and MP200 acoustic sources. The data were then batch processed through the clock correction, filtering, resampling, and pulse compression steps in the modified code.

The major task during the past year has been the detailed analysis of processed data from **PhilSea9** and **PhilSea10**. Although much work remains, eight (8) publications were authored and/or co-authored and accepted for publication in the Journal of the Acoustical Society of America, and others are in preparation. (See the Publications Section for details.)

Andrew White completed the requirements for the PhD degree in Geophysics at the University of Washington. These requirements included a thesis defense presentation at the APL/UW in August, 2013, and submission of his PhD thesis, titled “Underwater Acoustic Propagation in the Philippine Sea: Intensity Fluctuations”.

As part of our participation and support to the greater NPAL community we provided data and data processing assistance to several investigators. For example:
(1) We provided **PhilSea10** CTD and ADCP data to Dr. Steven Ramp at Soliton.
(2) We provided **LOAPEX** CNAV data to Dr. Percival at APL.
(3) We provided the following **PhilSea10** items to Dr. Gerald D'Spain at Scripps.
  (a) Developed code to calculate range and depth versus time from the echo sounder data; and provided the results.
  (b) Sent the DVLA raw and processed hydrophone data.
  (c) Sent the full ocean depth CTD data nearest the test drift in location and time.
  (d) Sent the parameters for the HX554 source during the drift test.

The NPAL North Pacific Ambient Noise Laboratory was installed in the early 1990s as part of the Acoustic Thermometry of Ocean Climate program and utilizes undersea hydrophone arrays owned by the US Navy. In addition, shore-based receiver equipment is located at a Navy shore facility. Complicating the transfer of data media and hardware components from the shore site to APL-UW are the required auditable trails of information on storage media and hardware. The current procedures, protocols, and documentation requirements devised and negotiated by APL-UW and Navy personnel for these transfers are described in Ref [2]. Due to the aging receiver equipment several equipment failures have occurred over the past year. We have copied the data from this period onto external drives and brought it back to APL. An extensive effort was made to identify and remove all the bad data files automatically generated during the failures. The remaining good files were then burned onto DVDs and stored in a classified room at APL-UW. All security paperwork was updated accordingly.

Following the Base Realignment and Closure action for NAS Barbers Point, the SOSUS cable termination building remained available as a shore site for several years until last year. All APL-UW equipment for this site was subsequently re-calibrated, removed and placed in storage in Hawaii. Application to a land-board was submitted to re-locate the receiver equipment over the cable route on Navy controlled property but no decision was forth coming. After a year in storage the equipment was given to the University of Hawaii.

NEW RESULTS

There has been significant progress on the analysis of data from **PhilSea9**. At the time of last year’s report, acoustic intensity arriving at the upper sub-array of the DVLA along three paths had been processed for three of its 30 hydrophones. Now receptions of these paths and one additional path at all 30 hydrophones have been processed.

At most of the hydrophones of the upper sub-array, it was possible to separate in time the energy arriving along four distinct paths from the transmitter to the DVLA. One path left the transmitter at a downward angle and had three turns before reaching the DVLA; this path was therefore designated ‘ID-3’: the ‘-‘ indicates a downward angle from the source and the ‘3’ indicates the three turns. The other paths were ID+4, ID-4, and ID+5.

At some depths, particular paths could not be separated from other paths. Acoustic intensity time series for paths with ID-3 and ID+4 at all hydrophones for which the paths were separable from other paths are shown in Figures 2 and 3. The plots for paths ID-4 and ID+5 are similar to the plot for ID+4, and are omitted here for brevity. Intensity fades of about 10 dB and with durations of approximately 18 and 12 hours, respectively, are visible at hydrophone depths greater than about 1150 m in path ID-3 during year days 118 and 119, shown in Figure 2. Similar fades are not observed in the time series for the other paths.

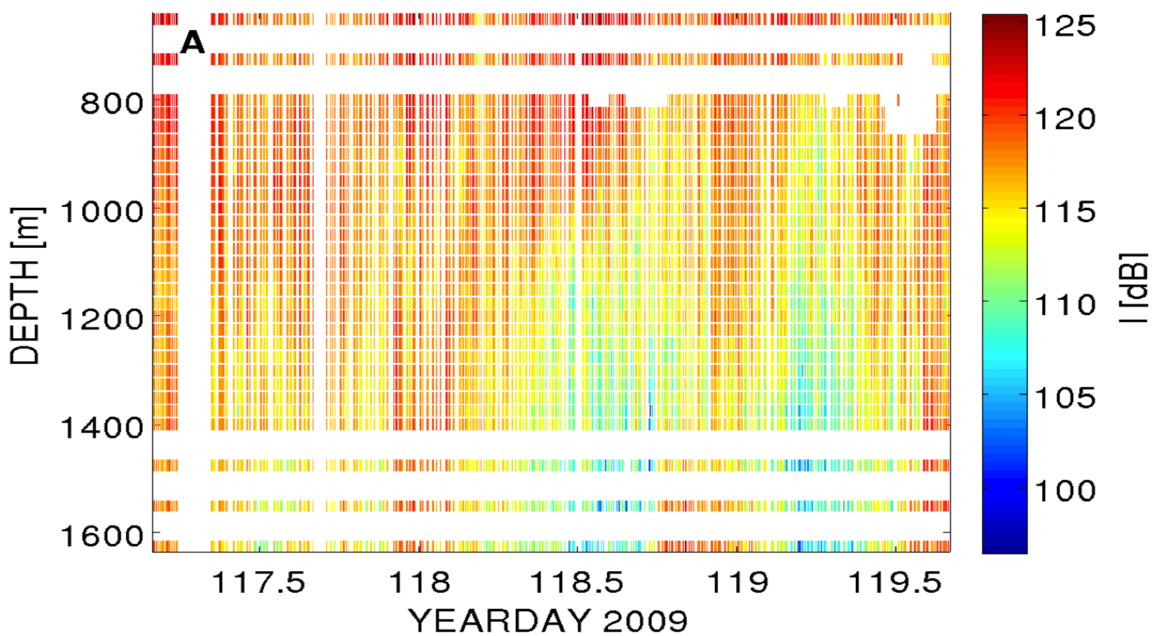

Figure 2. Measured intensities of all good receptions on the upper array of the DVLA for path ID-3. Intensity is represented by color in 22 m-wide bands in depth, centered on the depth of the corresponding hydrophone for clarity of presentation. At some of the shallowest hydrophones on the array, some further data were excluded—apparent here, and in figure 3 as white patches.

As was described in the annual report for FY2012, two Monte Carlo parabolic equation (MCPE) simulations were carried out (these were of multi-month duration and were still running at the writing of the FY2012 report). The purpose of these simulations was to determine if fluctuations in the intensity of the received signal, imparted by the oceanography of the Philippine Sea—which is characterized by energetic mesoscale and strong local internal tides—would be correctly predicted by a model composed only of a diffuse background of internal waves. In these simulations, the environment therefore consisted of a smooth, average background sound-speed profile plus random perturbations due to internal waves, as described by the Garrett-Munk ’79 [3] model.

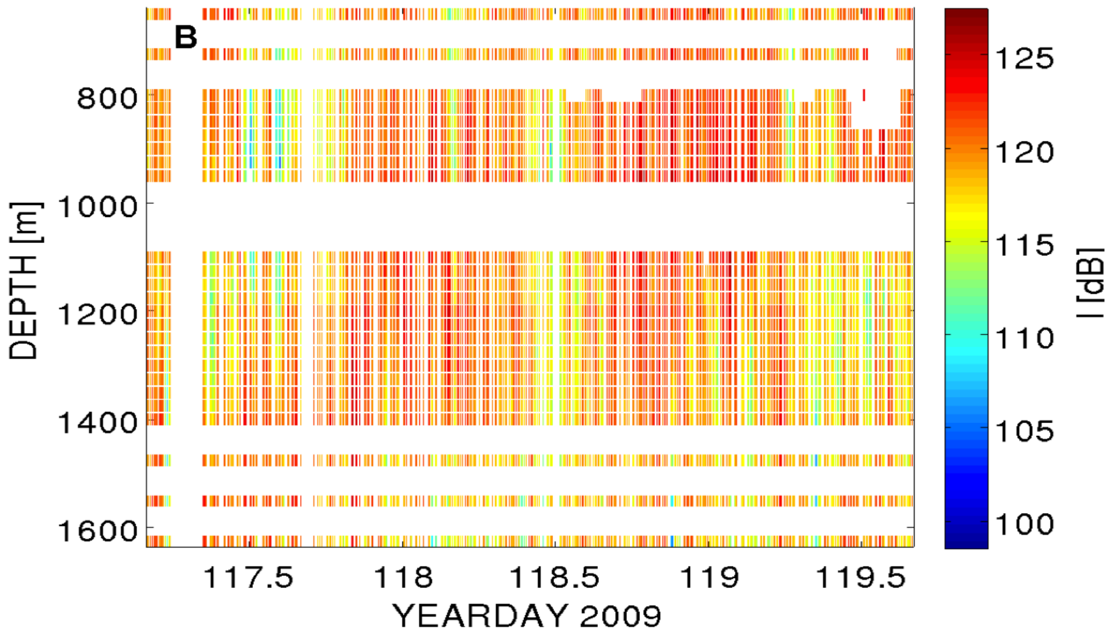

Figure 3. Measured intensities of all good receptions on the upper array of the DVLA for path ID+4.

In the first simulation, termed the 'time-independent' Monte Carlo Parabolic Equation (TI MCPE), 226 independent random oceans were constructed. In the second, termed the 'time-dependent' (TD MCPE) simulation, a single random ocean was evolved in time at a 240-s time-step for 320 hours (a total of 4800 time-steps). Broadband propagation through each ocean (or at each time-step) was computed and acoustic arrivals were separated in time in the same way as was done with the measured data. The only adjustment made to the Garrett-Munk '79 model was to set the variance of the internal wave displacements according to an estimate made from measurements taken by CTD instruments on the DVLA. An example set of time series from the TD MCPE simulation is shown in Figure 4. Time series for the other arrivals are similar, and are omitted for brevity.

The variance of the intensity normalized by the mean intensity squared is the scintillation index (SI), a fourth moment of the acoustic field. This moment was computed from the measured data and from the TI MCPE simulation for each path ID at all depths where paths were separable; the model-data comparison is shown in Figure 5. The rms log-amplitude, σ_ι, is also shown in the same Figure. The MCPE and data 95% confidence intervals on the SI and σ_ι overlap for ID+4, ID-4, and ID+5 at all hydrophone depths. The confidence intervals for data and simulation overlap for ID-3 for depths shallower than 1150 m, though the prediction is consistently slightly smaller than the measured value. The confidence intervals do not overlap for ID-3 for hydrophone depths deeper than 1150 m.

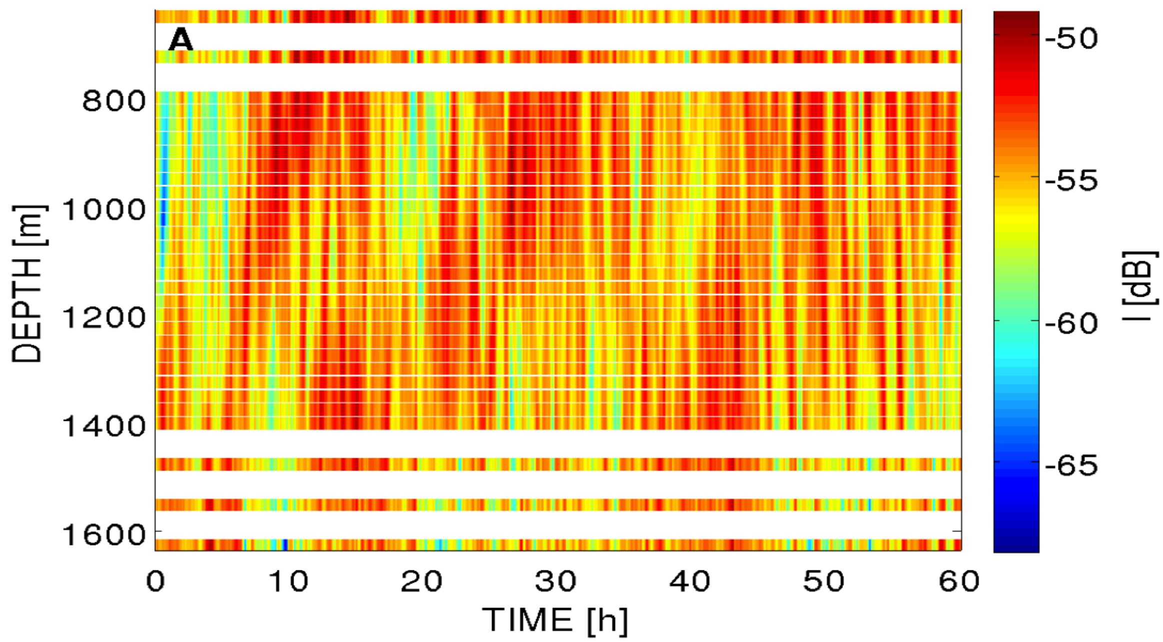

Figure 4. Shown here are 60 h out of the 320 h of simulated intensities of arrival ID-3. Time-series are computed at a vertical spacing of 1 m depth in the simulation, but only data at the hydrophone depths are shown here. Data have been spread over adjacent depths in the same manner as in the plots of the measured data in Figures 2 and 3.

Histograms of intensity normalized by the mean intensity computed from data and from the TD MCPE simulation are compared in Figure 6. Intensities at each depth were sorted into bins with a width of 0.05, and with bin edges ranging from 0 to 3.5. The resulting histogram counts were normalized by the total number of intensities that were recorded at that depth. For reference, 5% and 1% represent counts of 785 and 157, respectively, for the measured data, and 240 and 48, respectively, for the simulated data. The distributions of measured intensities exhibit depth-dependence and structure that appear to be consistent across multiple hydrophones. The distribution at several depths around 1300 m appears to be bi-modal for ID+4; the same is true at 725 m for ID-4, and at various depths for ID+5. The mode of the distributions of ID-3 are shifted increasingly with depth toward low intensities for hydrophones below about 1150 m, and the distribution widens with depth, with more high intensities on the deeper hydrophones. The low-intensity mode of the ID-3 distribution is consistent with the intensity fading seen in Figure 2.

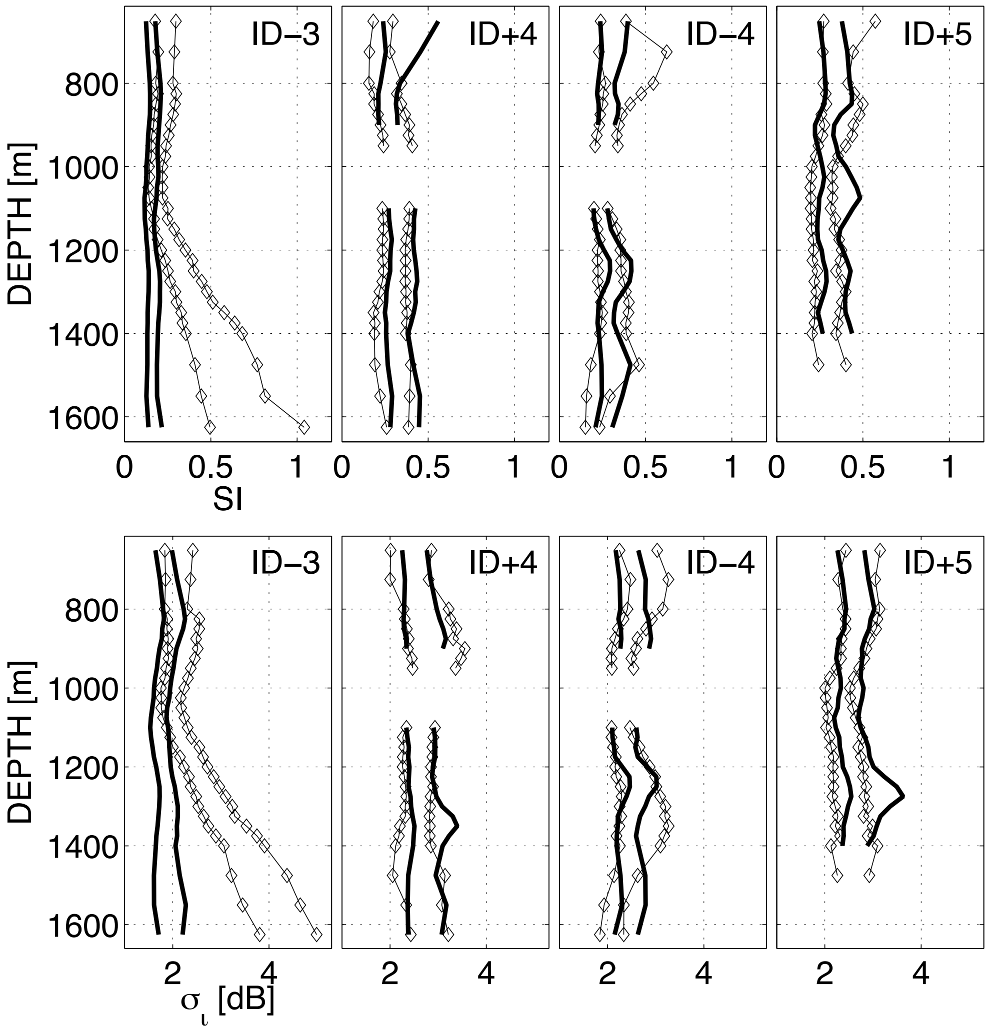

Figure 5. Top row: comparison of TI MCPE predictions of SI with measured values. The curves give the 2.5% and 97.5% percentiles—hence the 95% confidence intervals. Bold curves show the MCPE confidence intervals and curves with diamonds show confidence intervals on the measured values. Diamonds indicate the depths at which the measurements were made. The bottom row shows the same for σ_ι.

The distributions of the TD MCPE intensities are seen to be uni-modal for all four paths and at all depths for which paths could be separated. The MCPE distribution for ID-3 is noticeably narrower than for the other paths, apparent in the width of the light-blue portion of the histograms—as well as having a mode at a slightly higher intensity. The MCPE histograms appear otherwise to be quite similar to each other over the full range of receiver depths.

Despite the simplification of range-independence and the exclusion of internal tides from MCPE model simulations, the predictions of the SI, σ_ι, and the distribution of $I/\langle I\rangle$ for paths with UTPs below the extreme upper ocean generally agree with observations—the only model adjustment made was of the GM strength. This conclusion is in agreement with the results presented in Colosi et al. (2013) [4] (to the extent that the MCPE model provides a validation of the ocean

model), who studied the PhilSea09 environmental measurements more extensively. Their results were consistent with the GM spectral model's assumptions of horizontal isotropy and homogeneity (for diffuse internal waves), and they conclude that the GM spectrum could be used as an input to acoustic fluctuation calculations. The measures of intensity fluctuations studied here, the SI and σ_ι, did not appear to be strongly influenced by the number of UTPs in the path—though a compensating effect due to differences in UTP depth cannot be ruled out. Some of the differences between the distributions of the simulated and measured intensities may be due to the shorter duration of the measured timeseries; an experiment with a longer duration would be required to resolve the ambiguity. Enhanced variability in the form of long-period deep fades is observed for paths turning in the extreme upper ocean; this enhanced variability is not predicted by the MCPE model employed here.

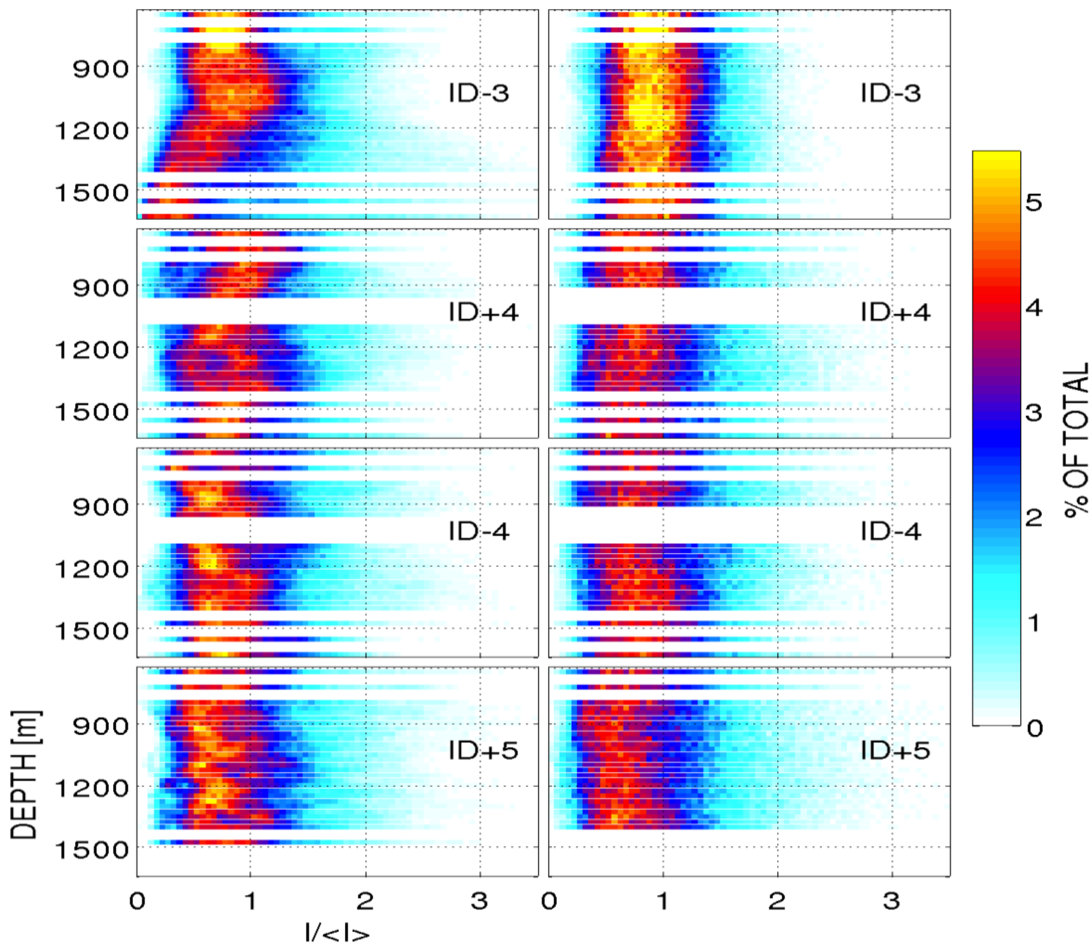

Figure 6. Shown in the left column are normalized histograms of $I/\langle I\rangle$ from the experiment. Shown in the right column are the same from the TD MCPE. Approximately 15 700 samples are included in the histograms at each depth for the measured data, while 4800 samples were included at each depth in the TD MCPE histograms.

Data from **PhilSea10** [1] and **LOAPEX** [5] were used to study the efficacy of using acoustic transmissions of m-sequence codes for underwater communication. Underwater communication has received intense activity for the past several years in the context of short-range high-frequency applications. Many of the developments parallel the sophisticated progress in cell phone technology. When long-range communication, e.g. 50 km or more, is required data rates suffer.

The potential use of widely distributed platforms for various applications has highlighted the requirements for reliable long-range underwater communication of platform commands. In these applications, however, data rates may not be that important. For example when sending pre-arranged commands between widely distributed platforms a simple three-bit code can identify eight commands. If each of the bits is a maximal length sequence, or m-sequence, high signal to noise ratios and low bit error rates are possible. In addition, if the two m-sequences are nearly orthogonal to one another, decoding the command is relatively simple. If sufficient time is available for command recognition, relatively long and repeated sequences can be used to increase signal to noise ratios and lower bit error rates.

In our NPAL research maximal length sequences, a.k.a. m-sequences [6] have been used with great success. Typically a low-frequency carrier of 50 to 250 Hz is phase modulated between two states to form a sequence. The pattern of phase shifts is determined by a code generator based on an octal seed number. A commonly used sequence includes 1023 bits and the phase angle modulation is given by the arctangent of the square root of the number of bits. The period of the sequence is then determined by the bandwidth of the transmitter. The broader the bandwidth, the fewer the cycles of the carrier required to form a single bit. For example, a projector with a 50 Hz bandwidth at a carrier frequency of 100 Hz requires two cycles of the carrier to form a bit of the m-sequence.

When processed with a replica of the transmitted code the received signal is compressed to a time resolution of one bit length. In the example above, two cycles of the 100 Hz carrier would provide a resolution of 0.02 s. This resolution can often provide temporal separation of much of the multi-path arrival structure. The processing gain is 10logN, where N is the number of bits in the code. Further gains may be achieved by coherently averaging repetitions of the sequence. Octal number code generators have been identified that produce nearly orthogonal codes, e.g. octal numbers 2033 and 3471. In other words, a received signal generated from 2033 and processed with a replica generated by 3471 produces no signal gain. Herein is the approach for a robust long-range, multi-path tolerant, simple three bit command code providing eight separate command codes. In this case the m-sequence, or repetitions of the same m-sequence, becomes the bit. For example, the command 101 might consist of 10 repetitions of code 2033 followed by 10 repetitions of code 3471, and finally 10 repetitions of code 2033.

Prior to examining real data we developed a methodology with simulated data. A m-sequence was generated in software having 1023 bits and a carrier frequency providing two cycles of the carrier for each bit. White noise was added to this signal to produce a signal to noise ratio of 4.89 dB. After low pass filtering the in-phase and quadrature components the phase of each bit is determined by an algorithm that examines the arctangent of the ratio of the in-phase component to the quadrature component. Results are shown in Figure 7 where the bit error rate was 1.86%.

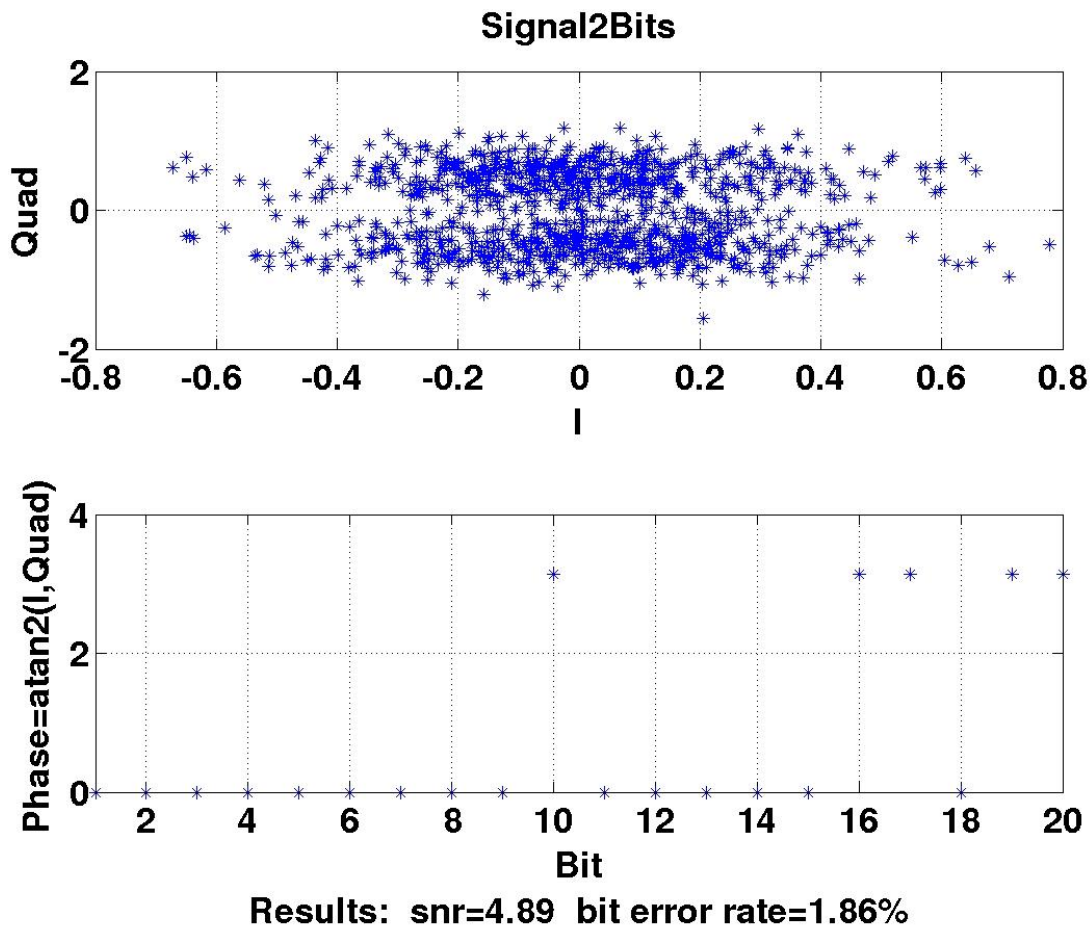

Figure 7. The upper panel shows the low-pass filtered quadrature components versus the in-*phase (I) components. The lower panel indicates the phase separation (times 4) for a selected number of bits. The bit error rate (proper phase separation) was 1.86% for all 1023 bits.*

In the case of real world data ambient noise is not the only problem. The transmitted signal is not ideal due to transducer limitations and the received signal will also be distorted due to ocean sound speed variability. Figure 8 shows the reception of a portion of the 8th m-sequence in a series of repeated sequences on hydrophone #7 of the upper array during **LOAPEX**. Figure 9 presents the results for the entire 1023 bit sequence after applying the methodology described above. The bit error rate for all 1023 bits in this case was 0.78%.

As mentioned above, it is typically possible to achieve additional gain by coherently averaging several m-sequences. Figure 10 presents results for **LOAPEX** transmissions from 50, 250, and 500 km to the 7th hydrophone of the upper array. The figure shows the improvement in average bit error rate by coherently summing 10 m-sequences (red stars) compared to using only one m-sequence (blue stars).

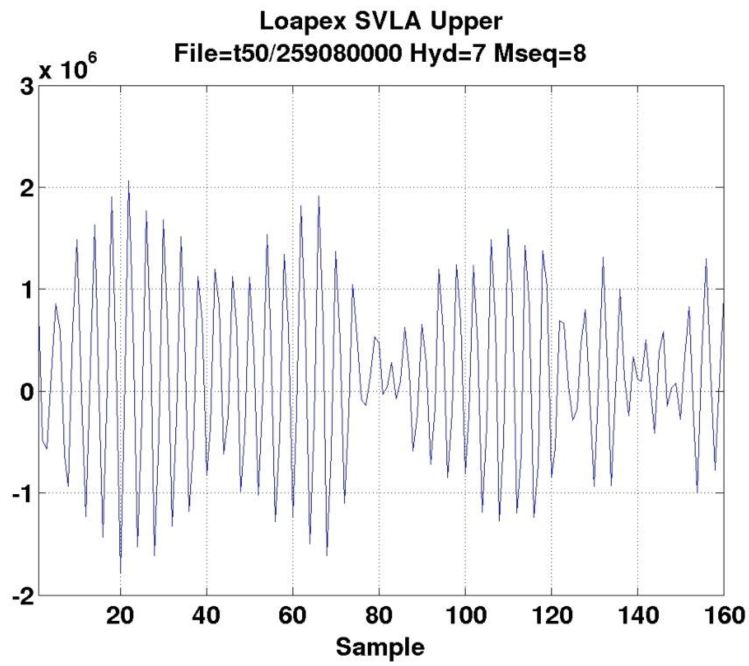

Figure 8. A portion of the 8th m-sequence as received on hydrophone #7on the upper array from a range of 50km during LOAPEX.

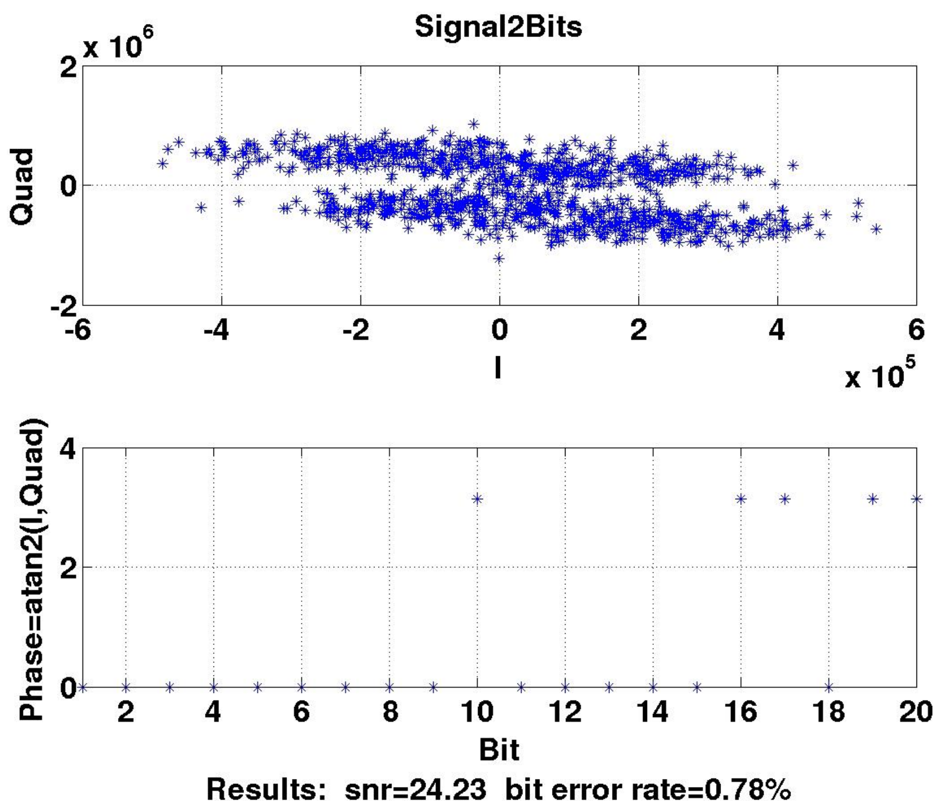

Figure 9. Similar to Figure 7 but with real data.

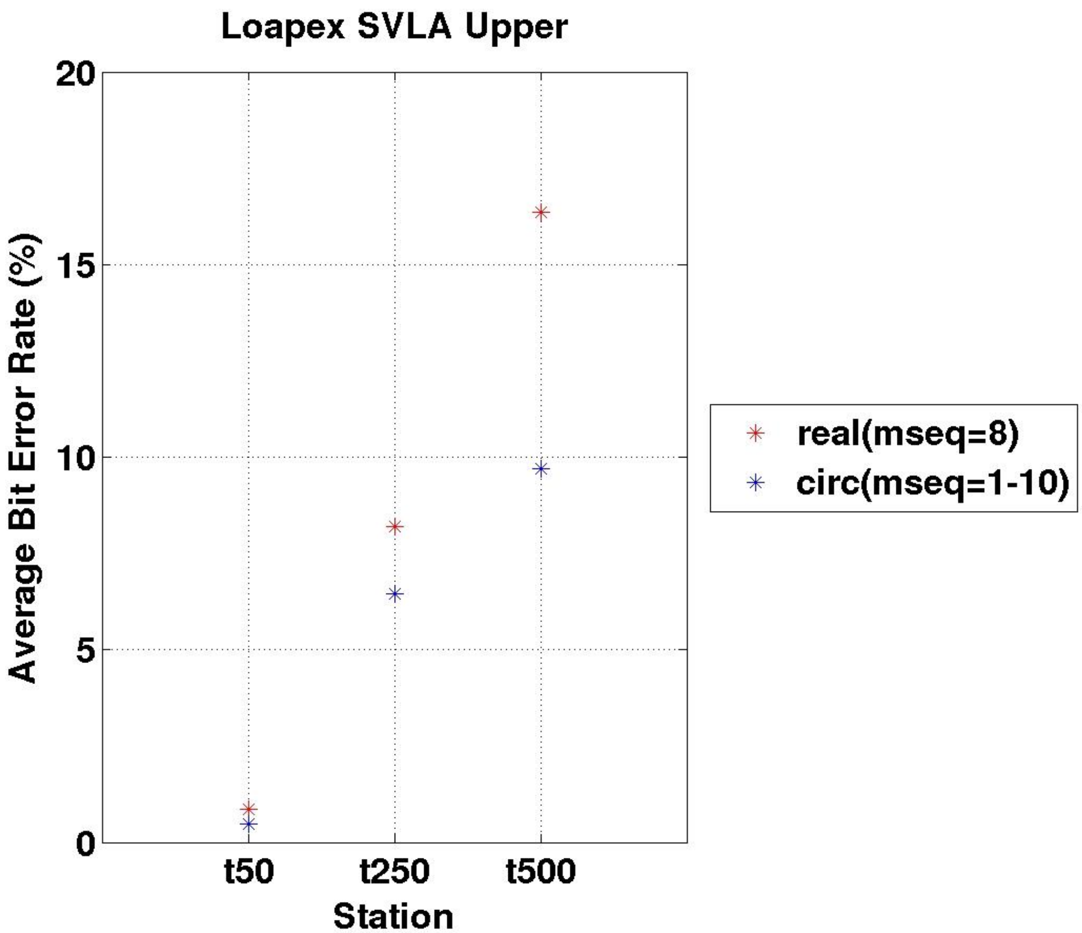

Figure 10. A comparison of average bit error rates at ranges of 50, 250, and 500 km, using a single m-sequence (red stars) and 10 coherently summed m-sequences (blue stars).

We examined the received signals in detail to determine when the bit errors occurred and found that the errors occurred most frequently when a bit containing only two cycles of the carrier was followed by another bit containing only two bits of the carrier. Fewer errors occurred when the transition involved at least one bit with more than two cycles of the carrier. The problem is related to the finite bandwidth of the transducer and the rise time of the signal following a phase transition.

Even with bit error rates of 10-20% it is relatively easy to identify the m-sequence when processed with the correct replica of the m-sequence. The scheme proposed to create an eight-bit code using nearly orthogonal m-sequences only requires the identification of the proper m-sequence. During the **PhilSea10** experiment two orthogonal m-sequences were simultaneously transmitted over a range of 500 km. When processed with the correct law, signal to noise ratios over 20 dB were observed. When processed with the incorrect law, the signals could not be detected. The two significant processing issues for this scheme are identifying the starting bit of each m-sequence, and if Doppler is present, a search in Doppler space must be conducted to

maximize signal to noise ratio. Nevertheless, it is practical to use nearly orthogonal m-sequences to send simple codes over very long distances.

COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), I. Udovydchenkow (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D'Spain (MPL).

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

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Chandrayadula, Tarun K., Kathleen E. Wage, Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, and Bruce M. Howe, "Reduced rank models for travel time estimation of low mode signals," *J. Acoust. Soc. Am.,* in press.

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(Note: Papers listed last year as submitted by Andy Ganse, Rex Andrew, and Frank Henyey were either rejected or are still in revision.)

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North Pacific Acoustic Laboratory and Deep Water Acoustics

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Award Number N00014-08-1-0843
Award Number N00014-13-1-0053
Award Number N00014-14-1-0218

LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) and Deep Water Acoustics programs at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of this research is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory and Deep Water Acoustics research are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. ***The North Pacific Ambient Noise Laboratory***, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consists of legacy SOSUS hydrophone receivers in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory.

The second avenue includes highly focused, comparatively short-term experiments.
We have completed a pilot study/engineering test and an experiment in the ***Philippine Sea*** called **PhilSea9** and **PhilSea10**, respectively [1]. See Figure 1. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the Distributed Vertical Line Array (DVLA) from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT).

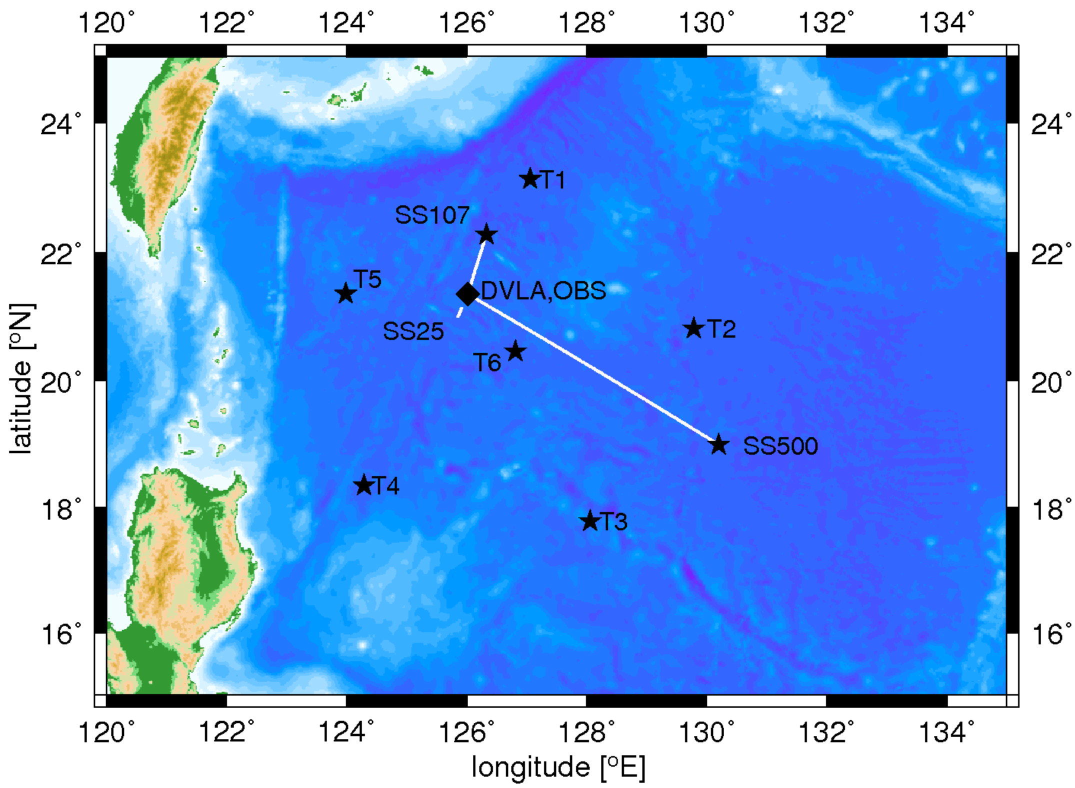

Figure 1. Principal activity locations for PhilSea9 and PhilSea10

WORK COMPLETED

I. Award Number N00014-08-1-0843

The PI's work on this grant was for the most part competed at the end of FY2013. Carry over funds amounting to approximately 2.5% of the total funding were extended to FY2014. The primary work with these funds was guidance and support to Andrew White as a new Post Doc.

In addition work was completed at the Barbers Point shore termination station, the Kauai transmitter station, and collaborative efforts with Gerald D'Spain at the Marine Physical Laboratory.

Due to the transfer of property from the US Navy to the State of Hawaii the Barbers Point shore termination station was closed. The contents of the station were removed and taken to the University of Hawaii Marine Facility. Most of the hardware was eventually scrapped but some was retained by the Marine Facility for future projects.

It was noticed in October 2014 that communications between APL-UW and the Kauai transmitter station had ceased. It was determined that the microprocessor responsible for selecting various hardware channels at the site had failed. A new microprocessor was installed and communications providing periodic hardware status have resumed. Transmissions from this site are no longer executed.

A collaboration with Gerald D'Spain at the Marine Physical Laboratory (MPL) has continued. Data from PhilSea10 during the Drift Test have corrected for Doppler shift, processed and provided to MPL. The collaboration will continue as the analysis progresses.

II. Award Number N00014-13-1-0053

In his two-year post-doctoral research proposal, Dr. White proposed to explore the possible roles of internal tides, surface mixed layers, and range-dependence in acoustic fluctuations that were measured during the PhilSea09 and PhilSea10 experimental efforts. He also proposed to process the PhilSea10 data. Completion of his doctoral degree delayed the start of the post-doctoral work until September 2013. In the intervening time, Dr. Rex Andrew's group had begun processing of the 2010 500 km data. Dr. White has collaborated closely with Dr. Andrew's group, and it was therefore decided that while the group processed the data, Dr. White would design and perform Monte Carlo Parabolic Equation (MCPE) simulations to be compared with the measured acoustic propagation data. Progress made thus far under the post-doctoral proposal has included analysis of a subset of the Conductivity-Temperature-Depth (CTD) measurements made at the Distributed Vertical Line Array (DVLA); design, construction, and completion of the broadband, 500-km-range MCPE simulations for center frequencies of 200, 300, and 81 Hz; and modeling of propagation through internal-tide perturbed environments involving background sound speed profiles both with and without near-surface mixed layers. More detailed descriptions of these efforts are below.

III. Award Number N00014-14-1-0218

This award provided guidance and technical support for Andrew White in his Post Doc efforts.

NEW RESULTS

I. Award Number N00014-08-1-0843 and Award Number N00014-14-1-0218

New results for these awards are recorded in New Results Section II.

II. Award Number N00014-13-1-0053

Internal Tide Simulations

Simulated internal-tide-perturbed sound speed environments were constructed for the purpose of exploring the possible variability in acoustic intensity that may be introduced by the tides. The environmental models consisted of plane waves traveling due East; the model included only the

first vertical eigenmode associated with the frequency of the diurnal tide. The first mode for the semidiurnal frequency is essentially the same as that for the diurnal, so some of the conclusions of the study will apply to both diurnal and semidiurnal tides. The difference between the tides at these two frequencies is in the range-dependence: the horizontal wave number for the diurnal tide is less than half that of the semidiurnal tide.

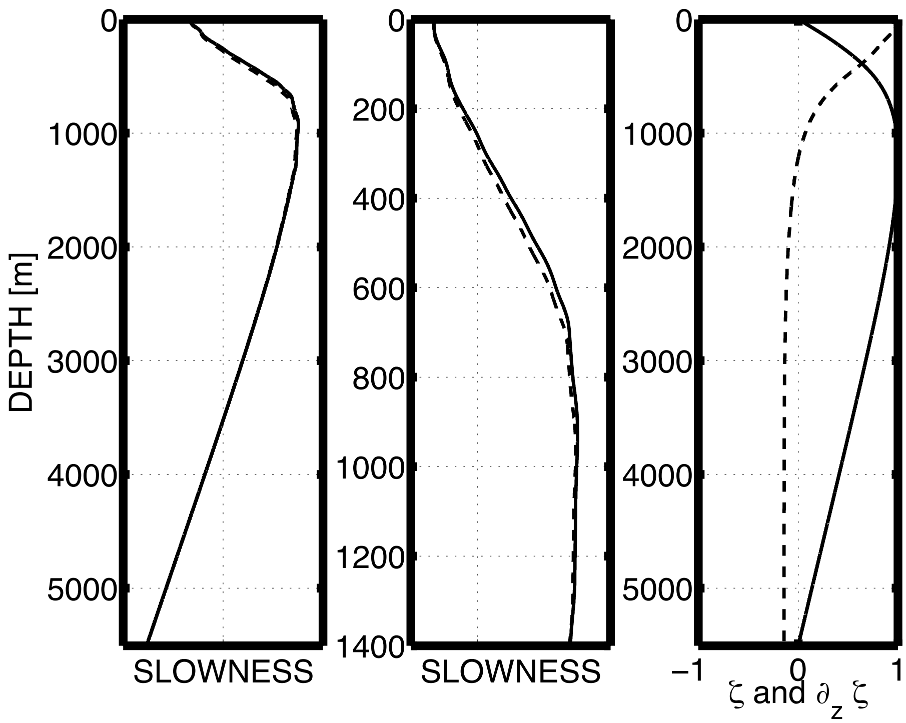

Figure 2. The slowness profile in the simulated internal-tide perturbed ocean at times that are 12 hours apart are shown in the left and middle panels; the middle panel is the same as the left, except that only depths down to 1400 m are shown. The first vertical displacement mode at tidal frequency is shown by the solid curve, and its derivative with respect to depth-the strain-shown by the dashed curve, appear in the panel at the right.

The first vertical mode is shown in figure 2, along with its vertical derivative (the strain) and with one of the sound speed slowness profiles used in this work. The slowness is shown at times that are 180 degrees apart in the tidal phase. The mode at this frequency causes a displacement of the same sign at all depths; the displacement is greatest near 1200 m depth, and decreases toward the ocean surface and toward the ocean bottom. The strain profile shows that the greatest strain occurs in the upper ocean, and then has the opposite sign at depths deeper than about 1200 m. The effect of this straining of the sound speed slowness profile is to decrease or increase, on average over depth, the first derivative with depth of the profile, with the greatest change occurring in the upper ocean.

The presence of mesoscale variability at the location of the PhilSea09 pilot study was seen in SSH measurements and corroborated with the CTD time series recorded by the CTD instruments on the DVLA [2]. Single profiles were low-pass filtered in the vertical to include only scales

larger than 100 m, and then used as representative range-independent background profiles to be perturbed by the internal tides in this study. Comparison of results between the different profiles provides information about the uncertainties caused by a limited knowledge of the background sound speed.

Broadband propagation through perturbed range-depth ocean slices was calculated using the Navy Standard Parabolic Equation (NSPE) code. The arrival corresponding to ray path ID-3 was windowed out from the resulting time fronts. This path exhibited intensity fades of 10 dB that lasted 18 and 12 h, respectively, in measurements obtained during PhilSea09 [2, 3]. An example of the simulated intensity profile vs. depth for path ID-3 at 1-h intervals spanning 24 h is shown in figure 3. Variability in intensity at a given depth is predicted to occur due to the mode-1 displacement of the slowness profile.

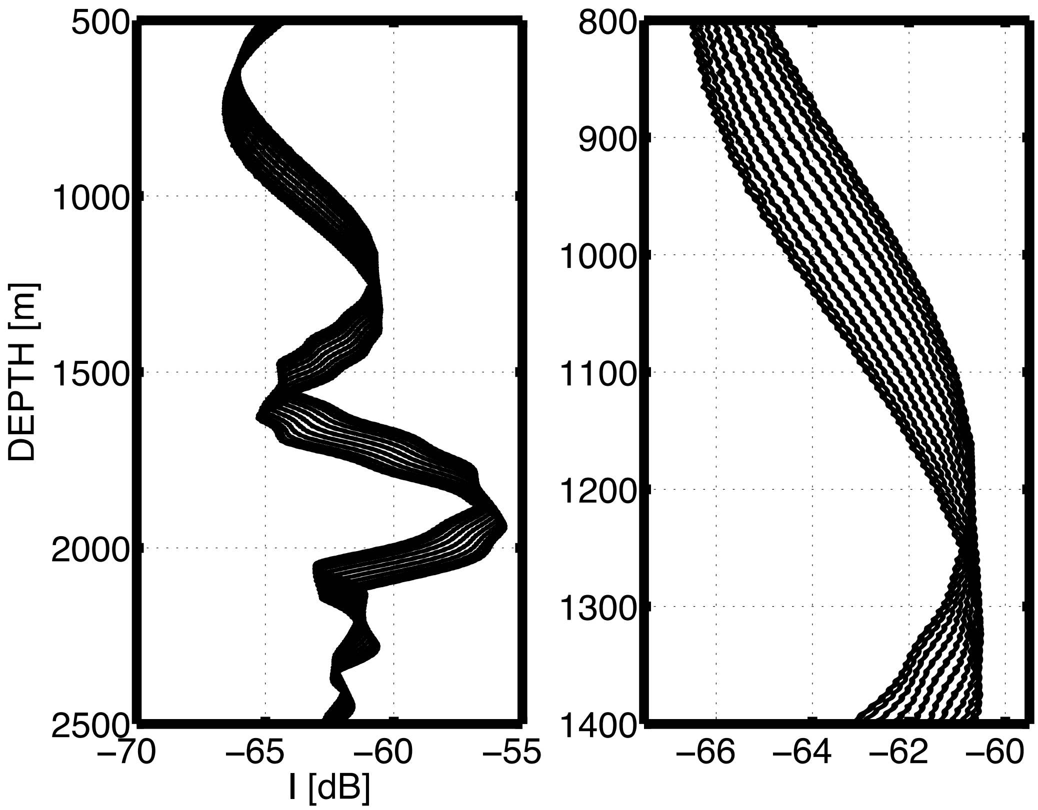

Figure 2. Intensity profiles calculated by the NSPE during the evolution of the mode-1 internal tide. The right panel is the same as the left panel, except that only depths from 800 to 1400 m are shown. Each curve is the intensity vs. depth at times separated by one hour; times spanning one diurnal tidal cycle (24 h) is shown here.

Propagation was then also calculated using a Hamiltonian ray-trace code that was developed previously by Dr. Frank Henyey. The parabolic equation (PE) is expected to contain all of the correct physics of the propagation, but what happens to the sound along its path is not revealed. When the ray-trace agrees with the PE, quantities associated with a given path that have been output all along the path then allow interpretation of the PE result.

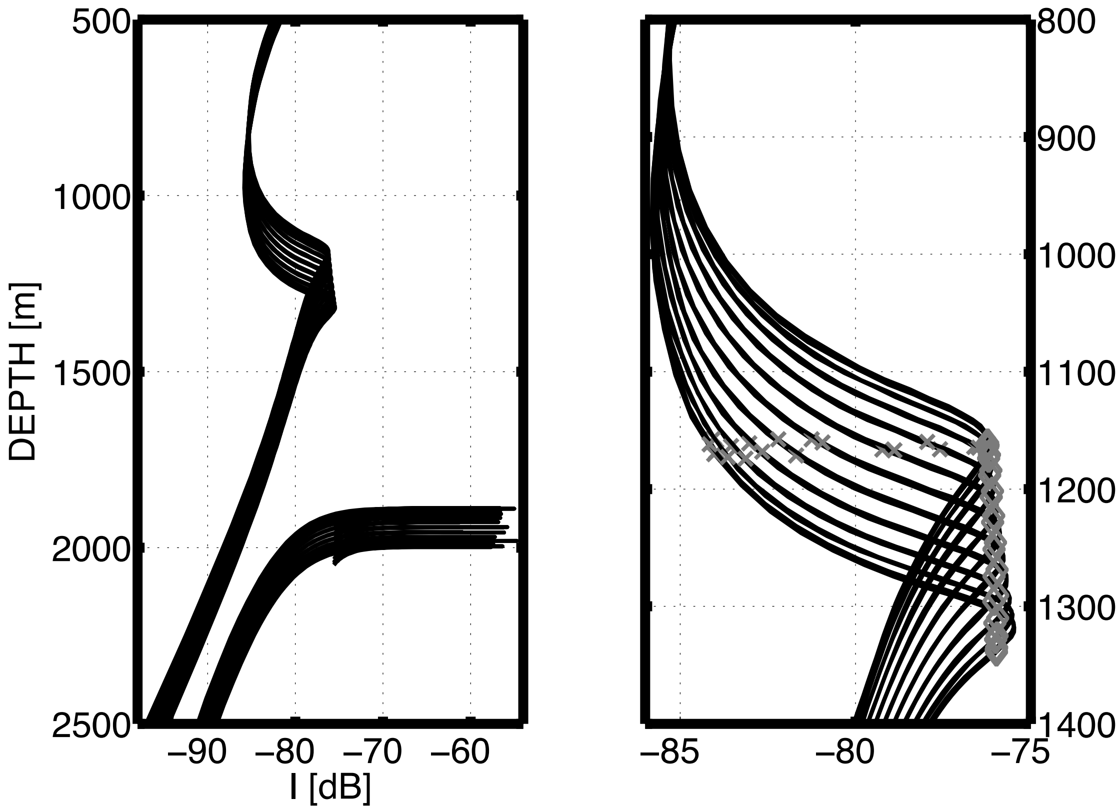

Figure 4. Intensity profiles calculated using Hamiltonian ray-tracing. The right panel is the same as the left, except that only depths from 800 to 1400 m are shown. The diamond-shaped symbols show the arrival depth and corresponding intensity of rays with the same initial angle, as the tide evolved.

The ray calculation does not capture all features of the intensity profile (see figure 4)—which is to be expected due to the infinite-frequency assumption inherent in a ray model. The high-intensity values at depths near 2000 m are due to a surface bounce. This study focuses on the rays composing the reasonably well-modeled local maximum in intensity around 1200 m.

It seems clear that the mode-1 internal tide causes the depth-dependence of the intensity to translate in the vertical while mostly retaining its shape in both the PE and ray calculations. Why is this the case? Analysis employing the Hamiltonian ray-tracing model provides some answers to this question, and leads to a deeper understanding of the effect of the internal tide on the acoustic intensity.

It is seen from the ray equations in the Hamiltonian formulation that the ray slope depends on the first vertical derivative of the slowness. The change in the average first derivative of the slowness caused by the straining of the internal tide causes a ray with a given initial angle to have a change in the average magnitude of its slope; the ray therefore arrives at a different depth at the end range.

It was also found from one of the equations in the Hamiltonian formulation that the rate of change with range of ray spreading for perturbations to the initial angle (ray intensity is proportional to the perturbation in vertical distance between the rays for small changes in initial angle) is dominated by a term containing the second derivative with respect to depth of the slowness. The turning depth of the rays is changed little by the internal tide displacement, meaning that the rays with the same initial angle turn through roughly the same slowness features at their Upper Turning Point (UTP) depth (which affects the intensity associated with the ray via the slowness' second derivative) throughout the tidal cycle. Thus the intensity associated with a ray with a given initial angle is expected to change little, while the depth-of-arrival at the end range changes significantly. These effects result in a vertical translation of the depth-dependence of the intensity profile, as seen in figures 3 and 4.

Dr. White has begun preparation of a manuscript that will present the work described above.

MCPE simulations

Displacements were computed from the CTD records for a month-long period of time, which included the time that the APL acoustic transmissions were made. Spectra were computed from these time series of displacement. The integral over the spectrum is equal to the variance of the displacement; this variance was used to determine the appropriate "GM strength ratio" [3, 4] to be used in the MCPE simulations. The strength ratio was found to be approximately 0.9—compared to the value of 1.6 as found from the same method for a similar time-period in 2009.

Dr. White performed a total of 240 broadband MCPE calculations (each, for three center frequencies of 81, 200, and 300 Hz) on a computer cluster, each through an independent realization of an internal-wave perturbed ocean. Arrivals corresponding to unique paths were windowed from the resulting time fronts. The arrivals and the depths at which they were extracted from the simulated time fronts are shown in figure 5. An undergraduate student who was working for Dr. Rex Andrew's group was tasked with organizing these windowed simulated arrivals into a database. Dr. Andrew's group also had the student create a corresponding database (for the 200 Hz signal, thus far) that was populated with arrivals measured during PhilSea10. The MCPE-simulated and the experimentally-measured databases will be shared between Dr. Andrew's group and Dr. White, facilitating various comparisons between MCPE and measurements.

COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), I. Udovydchenkow (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D'Spain (MPL).

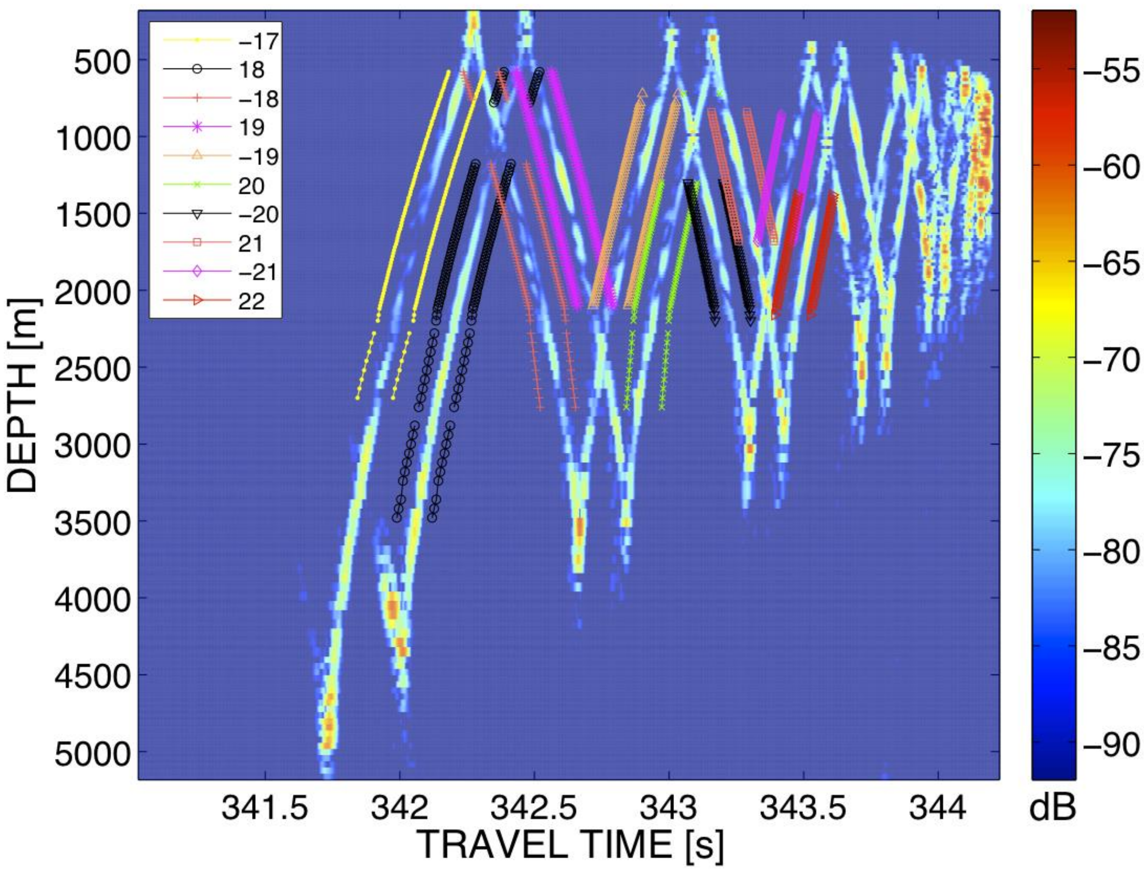

Figure 5. An example of the MCPE timefronts, including windows used to extract particular paths (associated with ID labels that are shown in the legend) from the simulated data. The simulated data was windowed only at the depths for which there are available measured data for comparison.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

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14. ABSTRACT

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions [illegible]. The approach toward equilibrium, as measure

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